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Variability and Predictability of West African Droughts: A Review on the Role of Sea Surface Temperature Anomalies

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ABSTRACT

The Sahel experienced a severe drought during the 1970s and 1980s after wet periods in the 1950s and 1960s. Although rainfall partially recovered since the 1990s, the drought had devastating impacts on society. Most studies agree that this dry period resulted primarily from remote effects of sea surface temperature (SST) anomalies amplified by local land surface–atmosphere interactions. This paper reviews advances made during the last decade to better understand the impact of global SST variability on West African rainfall at interannual to decadal time scales. At interannual time scales, a warming of the equatorial Atlantic and Pacific/Indian Oceans results in rainfall reduction over the Sahel, and positive SST anomalies over the Mediterranean Sea tend to be associated with increased rainfall. At decadal time scales, warming over the tropics leads to drought over the Sahel, whereas warming over the North Atlantic promotes increased rainfall. Prediction systems have evolved from seasonal to decadal forecasting. The agreement among future projections has improved from CMIP3 to CMIP5, with a general tendency for slightly wetter conditions over the central part of the Sahel, drier conditions over the western part, and a delay in the monsoon onset. The role of the Indian Ocean, the stationarity of teleconnections, the determination of the leader ocean basin in driving decadal variability, the anthropogenic role, the reduction of the model rainfall spread, and the improvement of some model components are among the most important remaining questions that continue to be the focus of current international projects.

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1. Introduction

West Africa is the westernmost region of the northern tropical African continent. The region is primarily characterized by distributions of rainfall and vegetation that are primarily zonal with strong north–south gradients, and it is considered as an entity in the meteorological context (Nicholson 2013). A monsoon season [the West African monsoon (WAM)] occurs every year, lasting from four to five months (May–September) near the Guinean coast and three months [July–September (JAS)] in the Sahel. Enhanced precipitation is associated with the seasonal northward migration of the intertropical convergence zone (ITCZ), where the northeasterly harmattan winds converge with the moisture-laden flow from the colder eastern equatorial Atlantic Ocean. Nicholson (2013) recently conducted an extensive review of rainfall variability over the Sahel and documented novel features of the region's storm circulations. Figure 1 (from Huffman et al. 2007) shows a latitude–time plot that illustrates the seasonal cycle of rainfall in West Africa. Rainfall rates increase along the Guinean coast of Africa (approximately 4°–6°N) throughout May, and precipitation remains high in this region through June. In the early summer [7 July, according to climatology compiled with the Tropical Rainfall Measuring Mission (TRMM)], rainfall decreases along the coast of the Gulf of Guinea and the rainfall maximum becomes established over the Sahel (about 10°–15°N). This sudden jump in latitude of the precipitation maximum represents the onset of the West African monsoon (Le Barbe et al. 2002; Sultan and Janicot 2003).

The number of scientific papers motivated by different aspects of Sahel rainfall has increased exponentially since the 1950s (see Fig. 2), from around 150 to more than 5000 entries in the period from January to May 2013. Droughts are major natural disasters for the largely rain-fed agriculture of most African countries. Particularly in the Sahel, a weak rainy season can create dramatic situations for millions of people (according to the International Federation of Red Cross and Red Crescent Societies; http://www.ifrc.org). The Sahel drought during the 1970s and 1980s was the most significant climate event at the continental scale during the twentieth century, and is arguably among the largest climatic changes worldwide (Trenberth et al. 2007). The event was associated with changes in the intensity, spatial distribution, and temporal evolution of the WAM and associated circulation features, such as the trade winds, African easterly jet (AEJ), and tropical easterly jet (TEJ) (Le Barbe et al. 2002; Sultan and Janicot 2003; Xue et al. 2004a; Dezfuli and Nicholson 2011).

The rainy season in the Sahel has large interannual and decadal variations. A substantial part of this variability is due to the influence of slowly varying climate subcomponents, such as sea surface temperatures (SSTs) and land surface conditions. The importance of oceanic influences at interannual and decadal time scales has been supported by the results of several studies (Folland et al. 1986; Palmer 1986; Rowell et al. 1992; Ward 1998; Camberlin et al. 2001; Giannini et al. 2003; Lu and Delworth 2005; Cook 2008; Caminade and Terray 2010; Losada et al. 2010; Rodríguez-Fonseca et al. 2011; Mohino et al. 2011a; Rowell 2013; Nicholson 2013). Other studies have addressed the effects of land–atmosphere interactions (Xue, 1997; Zeng et al. 1999; Nicholson 2000; Giannini et al. 2003; Yoshioka et al. 2007) and aerosol–radiative forcings (Kim et al. 2010). These effects can potentially interact with each other. For example, the variability of land surface conditions can affect the circulation over the ocean, which in turn can modify the SSTs and indirectly affect conditions over land (Ma et al. 2013).

The existence of significant impacts on WAM rainfall of slowly varying climate subcomponents indicates the potential for useful long-range forecasts (Vellinga et al. 2013; Gaetani and Mohino 2013; García-Serrano et al. 2013). To realize this potential with climate models, these must successfully reproduce the important characteristics of the WAM precipitation and circulation. Despite continuous model improvements in the models, a skillful simulation and prediction of the WAM, including its variability at different time and spatial scales and its association with external forcings, remains a daunting task.

The present paper surveys the literature on drought in West Africa and the Sahel with particular emphasis on recent work on these subjects. The text discusses the dynamical mechanisms linking anomalies in West African rainfall with those in SST over the World Ocean, the time dependence of these relationships, their predictability, and future projections. It is appropriate to acknowledge that many results presented in the following were obtained under the sponsorship of coordinated international research projects (see Fig. 2). The African Monsoon Multidisciplinary Analysis program (AMMA; http://amma-international.org/) has coordinated an ambitious program aimed to improve the knowledge and understanding of the WAM's variability and predictability on daily-to-decadal time scales, including climate change (Redelsperger et al. 2006; AMMA 2010; Ruti et al. 2011). The West African Monsoon Modeling and Evaluation (WAMME; Druyan et al. 2010) is a community initiative designed to evaluate the performance of state-of-the-art GCMs and regional climate models

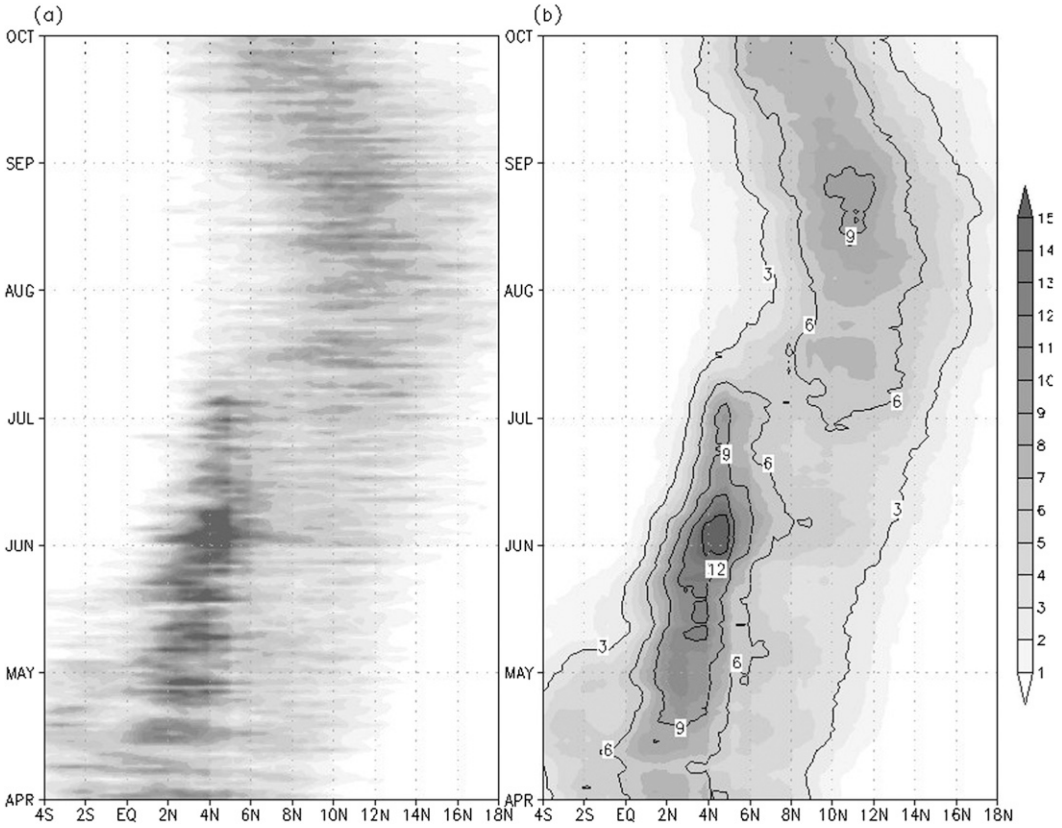

FIG. 1. Mean precipitation climatology (mm day^{-1}) for 1998–2012 from TRMM 3B42 V6 product (Huffman et al. 2007): (a) daily values and (b) with a 10-day smoothing applied. Values are averaged from 12°W to 6°E to avoid the precipitation maximum over the Cameroon highlands, where seasonal variations are different from those in regions to the west.

(RCMs) in reproducing WAM precipitation, drought scenarios, and their relevant processes. WAMME applies recently available observational and assimilation data for model evaluation and improvement (Boone et al. 2010; Xue et al. 2010b). The Coordinated Regional Climate Downscaling Experiment in Africa (CORDEX-Africa) has led to a coordinated evaluation of RCM skill, spread and uncertainties for simulating the West African monsoon mean climate and, to a lesser extent, its simulated onset and variability (Nikulin et al. 2012; Hernández-Díaz et al. 2013). The European Commission Seventh Framework Programme (EC FP7) Quantifying Weather and Climate Impacts on Health in Developing Countries (QWECI) project has aimed to understand, on a more fundamental level, the climate drivers of the vector-borne diseases of malaria, Rift Valley fever, and certain tick-borne diseases, all of which have major human and livestock health and economic implications in Africa (Cash et al. 2013; Tompkins and Ermert 2013; Ermert et al. 2013; Caminade et al. 2014). Some of these international projects have focused on the impact of SST anomalies on the WAM at interannual and decadal time scales. The collective findings from research sponsored by these projects have contributed significantly to progress, particularly in cases that occurred in the last few decades. Finally, phases 3 and 5 of the Coupled Model Intercomparison Project (CMIP3 and CMIP5) have addressed outstanding scientific questions in the Intergovernmental Panel on Climate Change (IPCC) Fourth and Fifth Assessment Reports (AR4 and AR5) process, improving understanding of climate and providing estimates of future climate change that will be useful to those considering its possible consequences.

The text is organized as follows. We start in section 2 and 3 by surveying the state-of-the-art knowledge of the SST influence on Sahel rainfall at interannual to decadal time scales, at which the variability of the ocean is the main driver of that in the atmosphere. Next, we summarize the progress in seasonal (section 5) to decadal predictability (section 6) and its skill in West Africa, following with an update of the future projections. A final section will summarize the most remarkable results, remaining questions, modeling issues, and future directions (section 8).

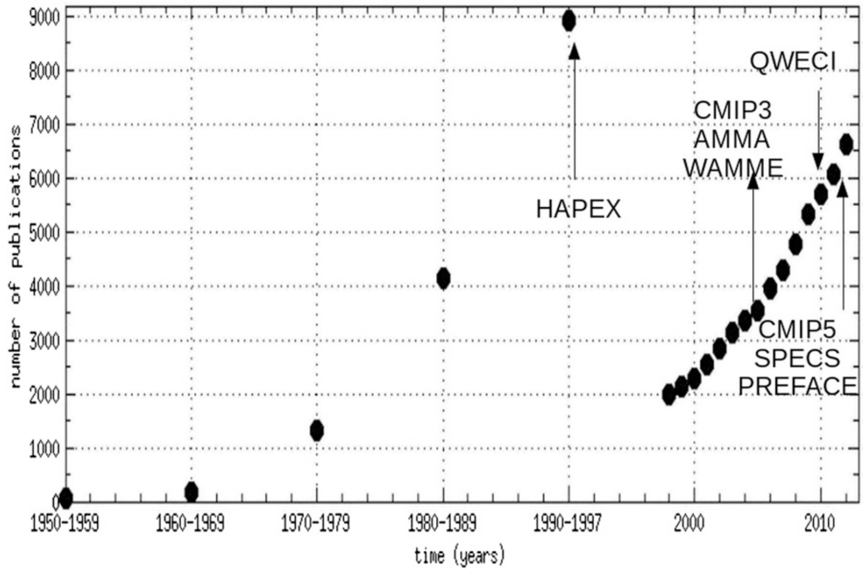

FIG. 2. Evolution of the number of papers published in relation to ''Sahelian rainfall'' from the 1950s (5 papers in the 1950s and 154 in the 1960s). In the last 15 years, the papers sum 63 840. From 1950 to 1997 data are plotted as averages over each decade; from 1998 onward data are yearly plotted. Source: Google scholar (http://scholar.google.com). Before 1990 units are in number of papers per decade, and after 1990 the units are number of papers per year. The dates of some of the most remarkable international projects studying the Sahelian climate variability are marked in the figure.

2. SST influence at interannual time scales

This section is dedicated to review recent findings on the influence of SST anomalies in different ocean basins (the Atlantic, Pacific, and Indian Oceans and the Mediterranean Sea) on the WAM precipitation at interannual time scales.

a. Influence of the tropical Atlantic Ocean

Since the early papers by Hastenrath and Lamb (1977), Lamb (1978), and Hastenrath (1984), many others have documented the tropical Atlantic influence on West African rainfall. This influence unfolds at different time scales: the variability in the equatorial and southern sectors affects that in interannual time scales, while that in the northern sector affects that in decadal time scales (Hastenrath and Polzin 2011).

At interannual time scales, the leading mode of tropical Atlantic variability is the Atlantic Niño, also known as the equatorial mode or zonal mode (Zebiak 1993; Carton et al. 1996). This coupled atmosphere–ocean mode is characterized by a warming (cooling) of the equatorial Atlantic during the boreal spring–summer in association with a relaxation (strengthening) of the trades and a deepening (shallowing) of the eastern equatorial thermocline. Several works using different methodologies have concluded that events of positive SST anomalies (Atlantic Niños) originate a dipole pattern of precipitation anomalies consisting of positive values along the coast of Guinea and negative ones over the Sahel (Horel et al. 1986; Wagner and da Silva 1994; Fontaine and Janicot 1996; Ward 1998). For a warming in the Atlantic, most AGCMs show how this dipole is the result of a weakening in the sea level pressure gradient between ocean and land and hence a weaker ITCZ shift, which is translated into more rainfall over Guinea and less rainfall over Sahel (Fig. 3, top). In the last decades, major international field programs, such as PIRATA (Servain et al. 1998), have sampled the tropical Atlantic and gathered important in situ data. Moreover, unprecedented information is been provided by instruments on board satellites. The resulting availability of homogeneous data in time and space has allowed for a better analyses of covariability between SSTs in the tropical Atlantic and rainfall in West Africa (Ruiz-Barradas et al. 2000; Vizy and Cook 2002; Giannini et al. 2003; Gu and Adler 2006; Reason and Rouault 2006; Polo et al. 2008). On the basis of data from the end of the 1970s, Polo et al. (2008) demonstrated that an Atlantic Niño can be associated with positive rainfall anomalies over the coast and negligible ones over the Sahel, as it could be expected from the dipolar structure in precipitation anomalies reported in previous studies (Fig. 3, bottom). Polo et al. (2008) also found that SST anomalies along

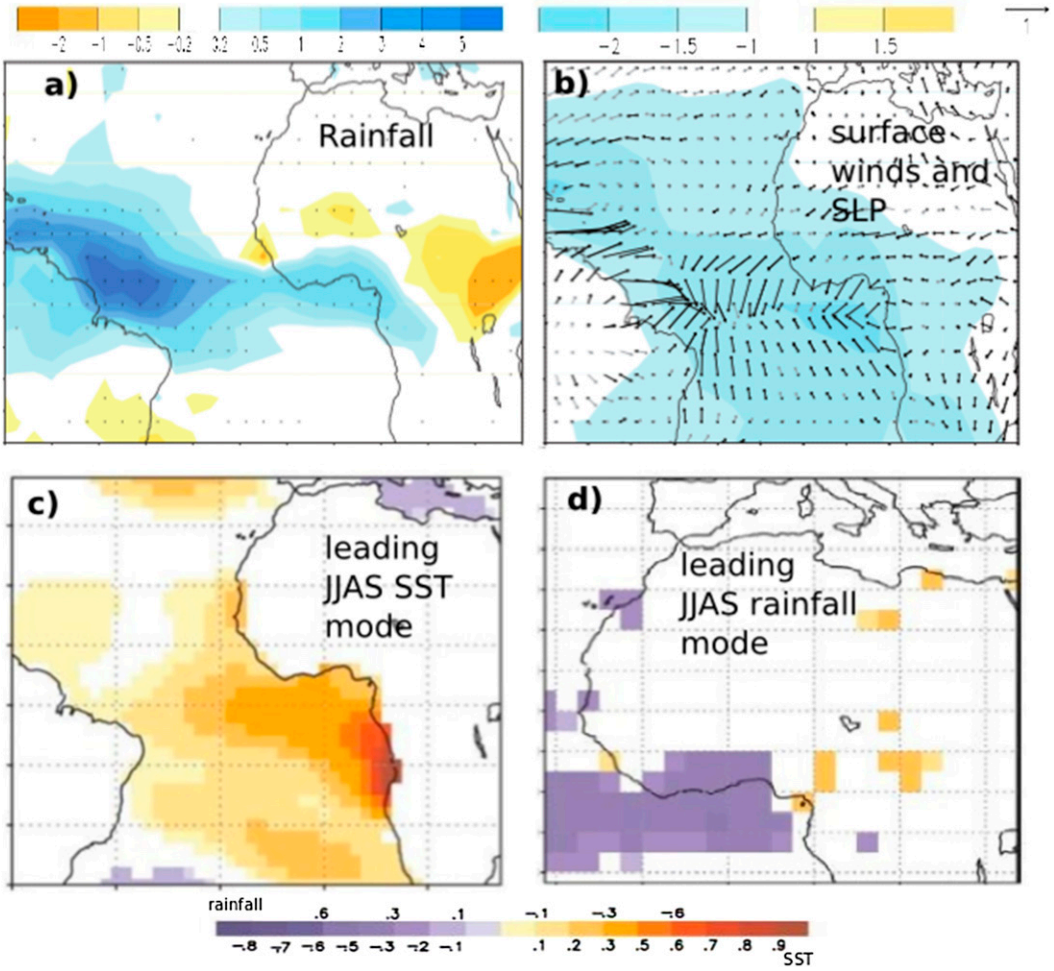

FIG. 3. (top) Ensemble of AGCM response to Atlantic Niño SST for four AMMA AGCMs in JAS with respect to the control run: (a) precipitation (mm day^{-1}) and (b) sea level pressure (SLP; hPa) and surface winds (m s^{-1}). Figure from results computed in Losada et al. (2010). (bottom) Leading mode of (c) tropical Atlantic SST from February–May (FMAM) to September–December (SOND) and (d) summer June–September (JJAS) precipitation over West Africa during the period 1979–2003. Only summer (left) SST and (right) precipitation (std dev in mm) patterns have been shown. Red colors are positive (negative) for the SST (precipitation) fields. Figure modified from Polo et al. (2008).

the equator in the northern summer were preceded in spring by anomalies along the Benguela coast of Angola in association with the Atlantic Niño, putting forward the potential predictability of the West African rainfall linked to the variability in the southern tropical Atlantic. Also, in this work, the presence of anomalies with different signs in the Pacific and Indian Ocean raised a hitherto unexplored possibility: the influence of these tropical oceans could interfere with the direct influence of the tropical Atlantic (Mohino et al. 2011b; Losada et al. 2012; Rodríguez-Fonseca et al. 2009, 2011).

Most current state-of-the-art atmospheric GCMs (AGCMs) are able to capture the links between SST anomalies and anomalous precipitation over West Africa using either observed global SSTs (Mohino et al. 2011b) or observed SSTs over the tropical Atlantic with climatology elsewhere (Vizy and Cook 2001; Wang 2002; Losada et al. 2010). Nevertheless, most coupled atmosphere–ocean GCMs of the current generation have important systematic errors in the tropical Pacific and Atlantic Oceans as they obtain too weak trades, a spurious ITCZ south of the equator, and too warm SSTs in the eastern part of the basins (Mechoso et al. 1995; Davey et al. 2001; Richter et al. 2014; Biasutti et al. 2006). Such errors compromise the successful representation of the WAM and its response to the equatorial mode (Joly and Voldoire 2010; Rowell 2013).

Complementary to works examining the impacts of SST anomalies in the tropical Atlantic, Nnamchi and Li

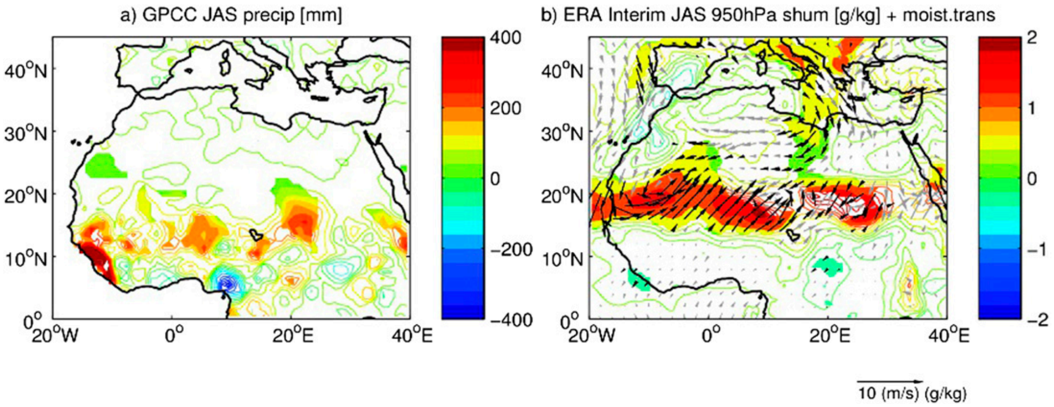

FIG. 4. JAS warm minus cold Mediterranean Sea composites: (a) GPCC precipitation (mm) and (b) ERA-Interim specific humidity (contours; $\mathrm{g\,kg^{-1}}$) and moisture transport at 950 hPa (arrows; reference arrow is $10\,\mathrm{m\,s^{-1}\,g\,kg^{-1}}$). Values in colored regions and black arrows indicate 90% significance regarding a Student's t test. Warm and cold events are identified on the basis of a standardized Mediterranean SST index (30°–40°N, 5°W–35°E) during the period 1991–2010. Warm and cold SST years correspond to 1994, 1999, and 2003 and 1993, 1996, 1997, and 2007 during which the index is >1 and <-1, respectively. The 1991–2010 period is chosen in order to exclude the turning of the Sahel precipitation trend in the 1980s and all the data are detrended.

(2011) highlighted the importance of anomalies in the subtropical South Atlantic together with temperature anomalies with the opposite sign at the equator forming a South Atlantic Ocean dipole. This configuration of SST anomalies would impact rainfall over the Gulf of Guinea coast via the so-called Lindzen–Nigam process (i.e., by enhancing anomalous divergence with opposite sign at both centers of the dipole). Venegas et al. (1997) and Trzaska et al. (2007) also discussed the relative importance of the South Atlantic in the tropical Atlantic variability.

b. *Influence of the Mediterranean Sea*

The finding of relationships between Mediterranean climate variability and WAM dynamics motivated a new line of research in the last decade. Rowell (2003) showed that positive SST anomalies in the Mediterranean Sea tend to be associated with similarly positive precipitation anomalies in the Sahel (Fig. 4a). He demonstrated that increased evaporation over the positive SST anomalies leads to increased moisture content in the lower troposphere, which is advected southward into the Sahel by the low-level flow across the eastern Sahara, resulting in stronger moisture convergence and precipitation over the Sahel. Figure 4b illustrates these features using recent observed and reanalysis data. By means of AGCM sensitivity experiments, Rowell (2003) showed that such increase in rainfall is then amplified by positive feedback mechanisms, such as 1) a more intense moisture inflow from the tropical Atlantic triggered by enhanced convective heating, 2) a reduced outflow of moisture from the midlevel African easterly jet, 3) an enhanced hydrological cycle, and 4) a larger rainfall contribution by African easterly waves.

More recently, a number of empirical and numerical studies have provided further support to the links between anomalies in Mediterranean SSTs and WAM precipitation (Jung et al. 2006; Fontaine et al. 2011b; Polo et al. 2011). Peyrillé et al. (2007) and Peyrillé and Lafore (2007) described the local circulations and mechanisms favoring the northward migration of the monsoon rainbelt. Fontaine et al. (2010) provided evidence that warm events over the Mediterranean Sea are associated with an intensified WAM, stronger low-level moisture advection, and a more northward location of ascending motions in West Africa. Moreover, they found that SST variations in the western Mediterranean Sea are associated with others in deep convection over the Gulf of Guinea, while those in the eastern Mediterranean Sea affect the atmospheric circulation over the North African subcontinent. Thus, anomalous eastern Mediterranean Sea warm conditions are linked to a northward migration of the monsoon system accompanied by enhanced southwesterly flow and weakened northeasterly climatological wind. Gaetani et al. (2010) explored these relationships at subseasonal time scales, showing that rainfall anomalies in the Sahel are concentrated in July–August when the monsoon circulation is fully developed inland, so that the effect of the northerly moisture transport from the Mediterranean Sea is maximized during that period.

c. *Influence of the Pacific Ocean*

At interannual time scales, a warming in the tropical Pacific tends to be associated with increased precipitation over the Gulf of Guinea and decreased precipitation over the Sahel (Folland et al. 1986; Rowell et al. 1995; Janicot et al. 1996, 1998, 2001; Ward 1998; Camberlin et al. 2001; Rowell 2001; Joly et al. 2007). Not all analyses before the 2000s, however, were supportive of this negative link (Kiladis and Diaz 1989; Ropelewski and Halpert 1989; Shinoda and Kawamura 1994).

In the framework of AMMA, experiments on the sensitivity of WAM rainfall to SST anomalies in the Pacific were performed for the period 1979–2002. In general, the results showed that positive SST anomalies in the Pacific SST have negative effects on Sahel rainfall (Mohino et al. 2011c). Figure 5 shows composites of rainfall differences between years with both warmer and colder than average SSTs in the Pacific Ocean (Mohino et al. 2011c). The relationships between SST anomalies in the Pacific and Indian Oceans with West African rainfall vary strongly with season, being different for May–June (Fig. 5, left) and for July–August (Fig. 5, right). In late spring, anomalous subsidence develops over both the Maritime Continent and the equatorial Atlantic in association with enhanced equatorial heating in the Pacific. Rowell (2001) interprets this feature as a stationary Kelvin wave response originating in the east Pacific. Precipitation increases over continental West Africa in association with stronger zonal convergence of moisture. In addition, precipitation decreases over the Gulf of Guinea. During the monsoon peak (July and August), the SST anomalies move westward over the equatorial Pacific and the two regions of subsidence during the previous months merge over West Africa, weakening the monsoon and thus rainfall over the Sahel.

It has been shown using observational data that links between anomalies in WAM rainfall and Pacific SSTs occur during the developing phase of an El Niño–Southern Oscillation (ENSO) event. That is, the anomaly in WAM appears in boreal summer before the peak of ENSO in autumn–winter. CGCMs have difficulties in capturing the temporal aspects of these connections, as shown by Joly and Voldoire (2009) for CMIP3 models. These model difficulties were attributed to shortcomings in the simulation of ENSO locking to the seasonal cycle and the associated atmospheric teleconnections.

d. *Influence of the Indian Ocean*

The Indian Ocean has important impacts on the Sahel at both decadal and interannual time scales. At interannual time scales, Biasutti et al. (2008) found substantial negative correlations between Sahel precipitation and Indian Ocean SSTs in observations and in CGCM simulations performed in the framework of CMIP3. Bader and Latif (2011) argued that the Indian Ocean SSTs were the main forcing for the drought over the western Sahel in 1983, presenting evidence that the dry conditions that persisted over the western Sahel in that year were mainly forced by positive SST anomalies in the Indian Ocean, which probably remained from the strong 1982/83 El Niño event. Except for 1983, however, SST anomalies in the Indian Ocean at interannual time scales are generally weak in comparison to the other basins. Thus, the impact of Indian Ocean anomalies on Sahel rainfall could be masked by that of other basins. Palmer (1986) analyzed the AGCM response to SST anomalies in individual ocean basins that correspond to those in the SST pattern for the global tropics used in Folland et al. (1986). The AGCM experiments showed that the Indian Ocean warming produces a slight rainfall enhancement over the western Sahel, but that the concomitant anomalies in the Atlantic and Pacific Oceans are responsible for the precipitation reduction in the west Sahel. Fontaine et al. (2011a) showed that positive SST differences between the Indian Ocean and the eastern Mediterranean Sea are synchronous with in-phase rainfall deficits over the whole Sudan Sahel. In addition, Rowell (2001) suggested that the impact of the Indian Ocean acts through changes in the large-scale gradient in SSTs from the west Pacific to the Indian Ocean. AGCM experiments showed that these changes lead to a stationary equatorial Rossby wave response over the Indian Ocean, causing anomalous subsidence over the Sahel.

e. *Modulation of the interannual variability by lower-frequency variations*

Studies performed in the last decades have argued that the impact of SST anomalies in some basins appear to be different depending on the decades considered. We will refer to this property as "nonstationarity."

The links between SST anomalies in the equatorial Atlantic and rainfall over the Gulf of Guinea are persistent features, but those with the Sahel rainfall seem to wane after the 1970s and at the beginning of the twentieth century. In these periods, the observations suggest that the influence of the Atlantic SST anomalies on the Sahel rainfall is balanced by concomitant SST anomalies with opposite signs in the Pacific and Indian Oceans (see Fig. 6). Joly and Voldoire (2010), Rodríguez-Fonseca et al. (2011), and Mohino et al. (2011b) have suggested that the counteracting effect of the Pacific could explain the absence of the dipolar relation with the Guinean rainfall reported before the 1970s. This hypothesis has been recently validated by the sensitivity experiments performed by Losada et al. (2012) with different AGCMs with prescribed SSTs in single or multiple ocean basins.

A similar tendency to nonstationarity appears in the impact of SST anomalies in the Mediterranean Sea. After removing the global SST trend during the twentieth century, Fontaine et al. (2011a) indicated that SST

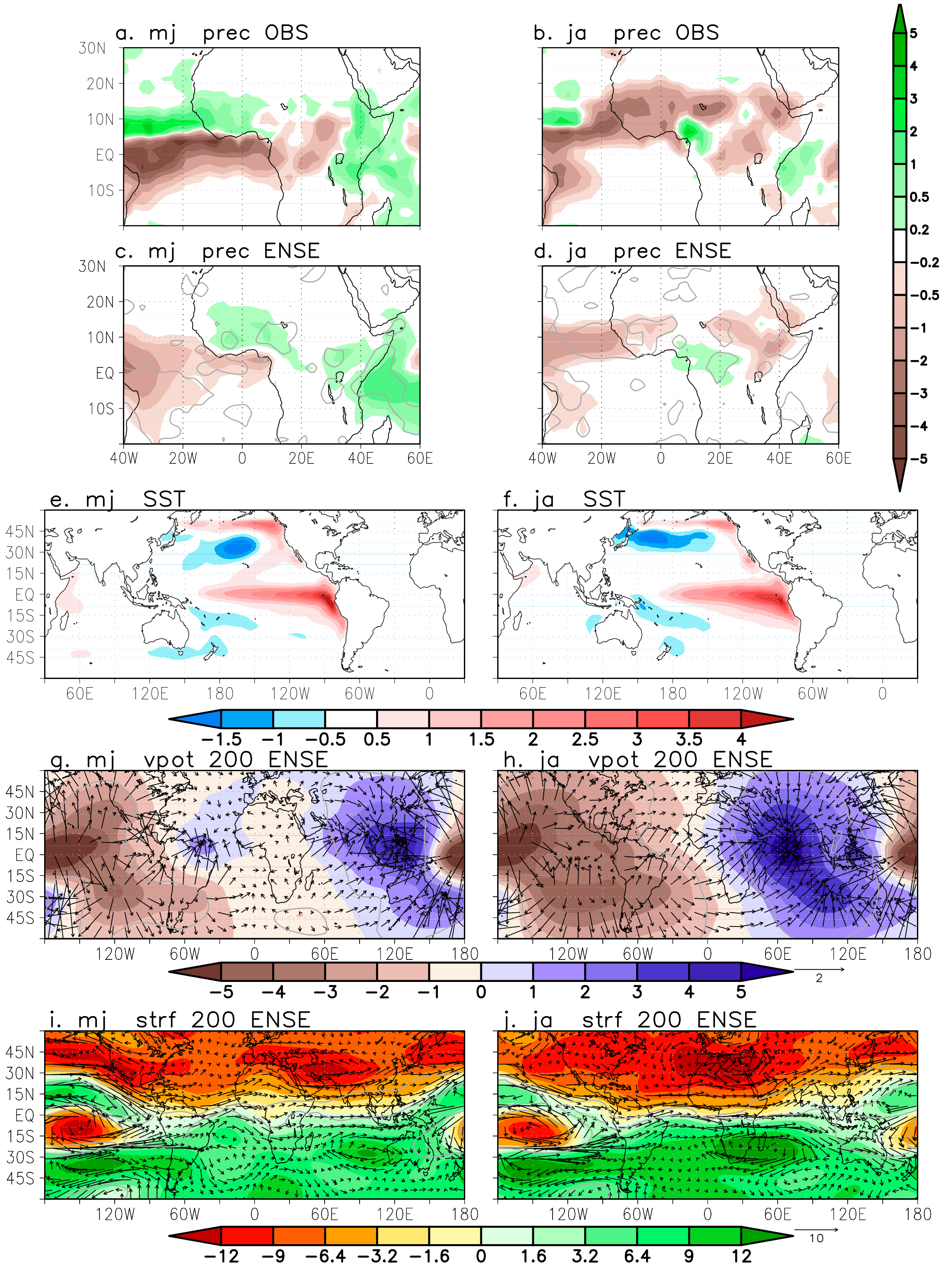

FIG. 5. (a),(b) Composite of anomalous observed rainfall (mm day^{-1}) in years 1983, 1987, and 1997 (“warm” Pacific years) minus 1985, 1988, and 1999 (“cold” Pacific years); (c),(d) linear component of the anomalous rainfall (mm day^{-1}) simulated by the four models’ ensemble mean obtained in the sensitivity experiments; (e),(f) anomalous observed sea surface temperature (K) used in the sensitivity experiments, obtained as a composite of warm Pacific years minus cold ones; (g),(h) as in (c),(d), but for the velocity potential (10^6 m^2 s^{-1}) at 200 hPa and divergent wind (m s^{-1}); (i),(j) as in (c),(d), but for the streamfunction (10^6 m^2 s^{-1}) at 200 hPa and rotational wind (m s^{-1}), all showing the average for (left) May and June and (right) July and August. Gray contours mark where the simulated anomalies are larger in magnitude than the intermodel standard deviation. Warm (cold) Pacific years were chosen as those in which the SST expansion coefficient for the first mode of covariability between Indo-Pacific SSTs and West African rainfall was above (below) the threshold of +1 (−1) std dev of the index. Figure modified from Mohino et al. (2011c).

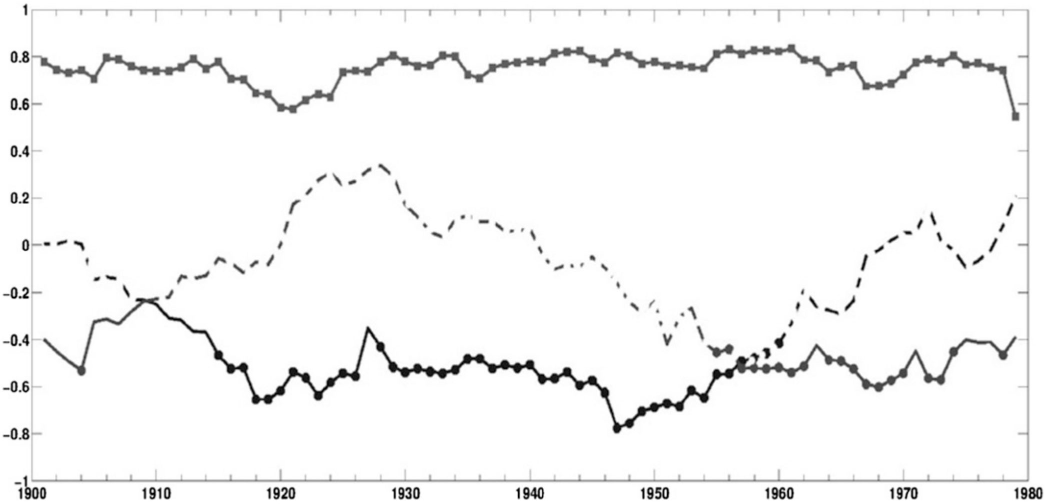

FIG. 6. A 20-yr sliding window running correlation between the Niño-3 and Sahelian rainfall indices (middle grey line), the Atl3 and Sahelian rainfall indices (bottom black line), and the Atl3 and Guinea rainfall indices (top continuous line) during June–September. Modified from Losada et al. (2012). Atl3 is defined as the SST area averaged over the region 3°N–3°S, 20°W–0°. Niño-3 is defined as the SST area averaged over the region 5°N–5°S, 150°–90°W. The Guinea index is defined as the rainfall area averaged over the region 8°–4°N, 20°W–10°E and the Sahelian index is defined as the rainfall area averaged over the region 20°–10°N, 20°W–10°E. Dots indicate the 20-yr windows in which the correlation is significant at 95% of confidence level.

anomalies in the eastern Mediterranean Sea and Indian Ocean have important effects on WAM rainfall, both in terms of intensity and time stability, with a growing importance of the Mediterranean Sea at the end of the twentieth century.

Broadly, two explanations have been offered for the nonstationarity of impacts. First, nonstationarity might be simply an artifact of sampling errors because some variation in the correlation between two variables can be expected by chance even during a stationary period of climate. Rowell (2013) addressed this hypothesis by applying a bootstrap resampling technique to SST teleconnections to African rainfall. He found no reason to reject the hypothesis that nonstationarity and multidecadal variability in the strength of these teleconnections might arise only from sampling variability, at least for the specific SST and rainfall in the regions considered. Internal atmospheric variability could also be relevant even at these longer time scales. For instance, Traore (2011) showed that running a AGCM over one to several centuries with fixed SST patterns (either the 1955–65 ‘‘moist’’ SST pattern or 1975–85 ‘‘dry’’ pattern) can provide decadal-scale rainfall anomalies up to 20% of the difference between the ‘‘moist’’ and ‘‘wet’’ long-term rainfall averages. Second, nonstationary teleconnections could be due to the slowly varying oceans and their multidecadal modes, as will be discussed later. These can alter the mean state of the atmosphere and/or the magnitude of SST variability in a way that during some decades the Atlantic influence interferes with that from the Pacific, whereas in other decades the Atlantic influence acts in isolation from the rest of the tropical basins (Mohino et al. 2011b).

3. Variability at decadal time scales

The first hypothesis on the prolonged Sahelian drought was that a decrease in vegetation cover led to increased albedo and, consequently, to enhanced subsidence in the region (Charney 1975). Later studies, however, identified the crucial role of SSTs over the world ocean in driving decadal Sahelian rainfall variability at decadal time scales. Using observed SSTs as boundary conditions, most AGCMs are able to reproduce the twentieth-century drying trend in West Africa and the Sahel drought of the 1970–80s and subsequent rainfall recovery (Rowell 1996; Giannini et al. 2003; Bader and Latif 2003; Lu and Delworth 2005; Haarsma et al. 2005; Hoerling et al. 2006, 2010; Lu 2009; Tippett 2006; Tippett and Giannini 2006; Caminade and Terray 2010; Mohino et al. 2011a; see also Fig. 8). The AGCM simulated impacts of SST anomalies on Sahel rainfall at decadal time scales, however, are weaker in comparison to the observations. This might be partially as a result of many reasons, such as shortcomings in the representation of vegetation–land–atmosphere interactions (Zeng et al. 1999; Giannini et al. 2003; Wang et al. 2004; Kucharski et al. 2013), changes in surface albedo (Kucharski et al. 2013), feedback with desert dust

(Yoshioka et al. 2007; Wang et al. 2012; Mahajan et al. 2012; Chin et al. 2014), and the atmosphere's internal variability (Traore 2011). Analyses carried out by the International Climate of the Twentieth Century Project (C20C) confirmed that SST variability is one, but not the only, driver of past Sahel droughts (Scaife et al. 2009). In this section we discuss separately the role of SST anomalies and land surface processes on the Sahel drought.

a. *Role of SST anomalies*

Decreased Sahel rainfall at decadal time scales has been associated with the warming of the tropical SSTs (Giannini et al. 2003, 2013; Lu and Delworth 2005; Mohino et al. 2011a). Hagos and Cook (2008) suggested that the combination of the SST anomalies over the tropical Indian and Atlantic Ocean basins was responsible for the 1980s Sahel drought and subsequent recovery in the 1990s. Caminade and Terray (2010) highlighted the role of the warming of the Pacific basin in reducing Sahel rainfall, while other works suggested that the drought was driven by the warming trend of the Indian Ocean basin during the late twentieth century (Bader and Latif 2003; Giannini et al. 2003; Tippett and Giannini 2006; Lu 2009). This warming of the tropical Indian Ocean and/or Pacific basin would induce enhanced convection locally and the propagation of Kelvin and Rossby waves that would communicate the tropospheric warming to West Africa (Chiang and Sobel 2002; Lu 2009). This would stabilize the region, leading to decreased rainfall over the Sahel through the so-called upped-ante mechanism (Neelin et al. 2003; Lu 2009; Caminade and Terray 2010). Lu and Delworth (2005) also suggested that the Pacific and Indian Ocean warming could lead to an anomalous Walker-type overturning cell with increased dry air subsidence over the Sahel and subsequent drought.

Alternatively, Sahel drought at decadal time scales has been related to the impacts of an interhemispheric dipole pattern of SST anomalies that is global, but most pronounced in the Atlantic basin (Folland et al. 1986; Palmer 1986). The differential heating of the Northern and Southern Hemisphere leads to a meridional shift of the ITCZ (Zhang and Delworth 2006; Kang et al. 2009; Hwang et al. 2013) and anomalous rainfall in the Sahel (Hoerling et al. 2006; Knight et al. 2006; Ting et al. 2009, 2011; Mohino et al. 2011a). Mechanistically, the movement of the rainbelt in the Sahel might occur through changes in the moisture content of the monsoon flow (Giannini et al. 2013) or circulation changes linked to a strengthening of the Saharan heat low (Martin and Thorncroft 2014a).

The relative importance of SST anomalies in different basins on Sahel rainfall has been greatly debated (e.g., Hoerling et al. 2006; Giannini et al. 2003; Bader and Latif 2003), partly because the sensitivity to each basin appears to be highly model dependent (Scaife et al. 2009; Biasutti et al. 2008) and partly because the details of the warming pattern matter greatly (Hagos and Cook 2008). Yet, recent work by Giannini et al. (2013) suggests that these differences might be reconciled by assuming that Sahel rainfall responds to relative changes between SST anomalies in the northern Atlantic and the entire tropics.

The broad agreement of the scientific community on SST anomalies being crucial drivers of Sahel rainfall decadal variability during the twentieth century has spurred a lively debate on whether this variability might be due to external forcings (anthropogenic and natural emissions) or to internal climate processes (natural variability modes) or, more likely, to a combination of the two. Recently, Mohino et al. (2011a) interpreted the pattern of SST variations linked to SST rainfall changes as a combination of three different modes of SST decadal variability: the response to the global warming trend, the positive phase of the interdecadal Pacific oscillation (Zhang et al. 1997), also known as the Pacific decadal oscillation (Mantua et al. 1997), and the negative phase of the Atlantic multidecadal oscillation (AMO; Knight et al. 2005), with all three leading to reductions in Sahel precipitation. Some works suggests that the observed AMO is an internal mode of variability not explained by external forcings (Knight et al. 2005; Knight 2009; Ting et al. 2009; 2011), while others point to the role of anthropogenic aerosols in cooling the North Atlantic more than the South Atlantic (Rotstayn and Lohmann 2002; Biasutti and Giannini 2006; Kawase et al. 2010; Ackerley et al. 2011; Biasutti 2011). Recently, Booth et al. (2012) showed that their CGCM experiments could simulate most of the observed twentieth-century SST variability in the North Atlantic, and that this variability was highly dependent on the indirect effect of aerosols. However, Zhang et al. (2013) call into question these results as there are multiple inconsistencies between the previous experiments and key aspects of observed variability within and without the North Atlantic.

Hoerling et al. (2006) and Lau et al. (2006) analyzed historical simulations of CGCMs participating in the CMIP3. Overall, the models failed to simulate the mid-twentieth-century Sahel drought and recent recovery (Hoerling et al. 2010) with the correct magnitude and timing, suggesting that anthropogenic forcings played little or no role in driving the drought. On the other hand, Held et al. (2005) showed that the GFDL CM2.0 and CM2.1 coupled models could very well reproduce the observed drying trend during the second half of the twentieth century. Ackerley et al. (2011) suggested that although the aerosols contributed to the intense decline in the rainfall over the Sahel in the 1950–80 period, a fraction of this drying could be related to either the effect of an internal mode (AMO) or climate model deficiencies. Biasutti and Giannini (2006) estimated from historical CMIP3 simulations that anthropogenic forcing, especially by aerosols, may have contributed a third of the long-term twentieth-century drying, and that estimate has been confirmed by CMIP5 models (Biasutti 2013). Recently, Hwang et al. (2013) posited that both the drought and subsequent recovery in the Sahel are greatly influenced by the increase and subsequent reduction of sulfate emissions in Europe and North America. However, neither generation of CMIP climate models reproduces the magnitude of the observed rainfall variability at decadal to multidecadal time scales over the twentieth century. Dismissing a strong role of natural variability in driving droughts at time scales less than a century might thus be premature (Biasutti 2011). This point of view is strengthened by paleoclimate and historical studies, which have highlighted how recent droughts in the Sahel are not unprecedented (Shanahan et al. 2009; Brooks 1998; Nicholson 1978, 1979; Nicholson et al. 2012). Shanahan et al. (2009) highlighted the existence of intervals of severe drought lasting for periods ranging from decades to centuries over Ghana over the last 3000 years and they related these megadroughts to the AMO. Prolonged drought episodes lasting from 1100 to 1500 might have partly contributed to the collapse of the Malian empire (Brooks 1998); multidecadal droughts were also reported in Senegambia from 1710 to 1750 and from 1770 to 1780 followed by reported mass starvation from 1790 to 1840 (Nicholson 1978, 1979, 2013). The Sahel drying observed during the second half of the twentieth century appears to be neither unusual nor extreme from a paleoclimate perspective or considering the long-term historical context.

Analyses of simulations by recent generations of CGCMs have provided additional insight on the WAM and its variability (Fig. 7). Control runs, historical simulations, future projections, and seasonal-to-decadal predictions have been analyzed. Rowell (2013) has recently assessed the capability of Sahel models to represent WAM teleconnections. His work suggests that some teleconnections tend to be poorly reproduced (e.g., those with the equatorial Atlantic SSTs and the Pacific ENSO), while others seem to be captured by most models (e.g., the link between the Mediterranean SSTs and Sahel rainfall).

b. *Role of land surface processes*

Pioneer projects as Hydrological Atmospheric Pilot Experiment (HAPEX) in the Sahel (Goutorbe et al. 1997) made a contribution to understanding the land surface processes in relation to the WAM variability. Since then, several studies have addressed the role of land surface processes in driving Sahel drought. Land surface parameterizations in the atmospheric models used in these studies cover a wide range of complexity (e.g., Laval and Picon 1986; Sud and Molud 1988; Xue et al. 1990; Eltahir and Gong 1996). Nevertheless, the results on sensitivity to land conditions in Sahel were quite consistent across models. Increases in albedo (soil moisture) produce negative (positive) feedbacks on rainfall, even the magnitude of the impacts is within a narrow range (Xue and Fennessy 2002). A proper evaluation of the surface feedback to climate can be obtained only when all relevant components of the surface energy and water balances are taken into account.

The impact of land degradation upon regional climate seasonal variability and drought events over the Sahel has been explored using a GCM coupled to a biophysical model (Xue et al. 2004a). According to the results, the primary effect of degrading savanna and shrub conditions in the Sahel is reduced evaporation. This is partially due to reduced net radiation because of higher albedo, but more importantly to lower leaf area index (LAI) and surface roughness length, and to higher stomatal resistance. The reduction in evaporation results in less convection and lower latent heating rates in the troposphere, in association with a relative subsidence, which in turn weakens the monsoon flow and reduces moisture flux convergence and lowers rainfall.

It has also been found that the Sahel, along with a few other regions that are mostly semiarid, has the largest soil moisture/climate coupling strength in the world. This result was obtained in the Global Land–Atmosphere Coupling Experiment (GLACE; Koster et al. 2006). Two sets of boreal summer (June–August) simulations were performed with multiple GCMs. In one, moisture varied during the simulations, while in the other set the same geographically varying time series of subsurface soil moisture was prescribed. The soil moisture–atmosphere coupling strength in each model was then estimated with a statistical method. The high soil moisture–climate coupling strength in the Sahel is consistent with a number of soil moisture feedback studies (e.g., Douville 2002; Philippon and Fontaine 2002). Results based on CMIP3 simulations also show that North Africa is another region with strong soil moisture feedbacks (Notaro 2008). A few modeling studies have shown that the root-zone soil moisture might not act as a memory of rainfall anomalies for the following rainy season and therefore might not affect the persistence of the drought (Shinoda and Yamaguchi 2003; Douville, et al. 2007; van den Hurk and van Meijgaard 2010).

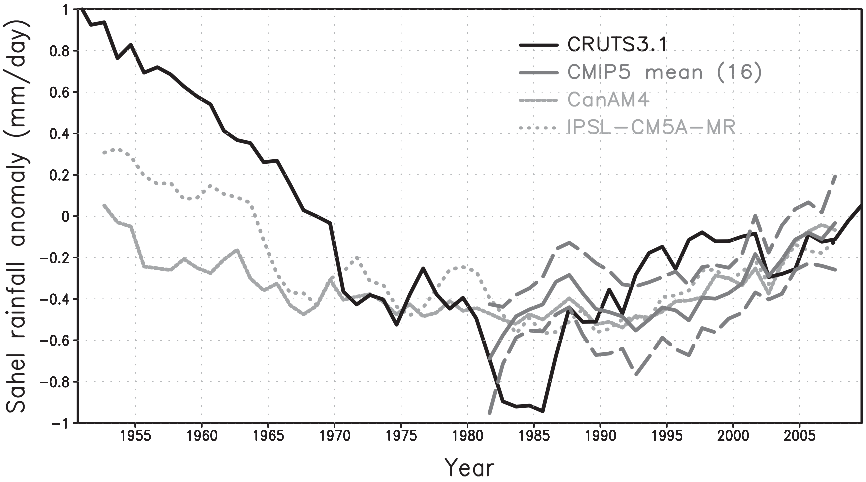

FIG. 7. Seasonal (July–September) anomalies of rainfall over the Sahel (10°–20°N, 10°W–10°E) calculated from the CRU time series, version 3.1 (TS3.1), dataset (Harris et al. 2014) (black solid line), an average of 16 AGCM models forced with observed SSTs (dark gray solid line), CanAM4 (light gray solid line), and IPSL-CM5A-MR (light gray dotted line). Data have been smoothed with a 5-yr running mean to focus on decadal time scales. Dashed dark gray lines show the one standard deviation of the 16 CMIP5 AMIP models. Simulated data were obtained from the CMIP5 database. AMIP simulations in CMIP5 start in 1979. Only two models started in 1950s, which are plotted separately in the figure.

The impact of the vegetation biophysical processes (VBP; i.e., land surface processes relevant to climate interactions associated with vegetation) on the WAM has also been investigated by Xue et al. (2004b, 2010b), who analyzed the results from two AGCMs coupled to three different land models with varying degrees of physically based complexity in the representation of VBP. The criterion to assess the importance of VBP effects was based on the simulation skill in reproducing the observed global precipitation under the assumption that their inclusion would improve precipitation simulations. Figure 8 shows the reduction in absolute seasonal mean bias of 5-yr mean simulated precipitation (or improved prediction skill) due to VBP processes. Accordingly, West Africa has the largest VBP impact in the world, especially in summer (see also Ma et al. 2013). Using remotely sensed LAI datasets, compared with using LAI based on a few ground surveys, in the boundary conditions of a GCM produced substantial improvements in the near-surface climate in West Africa (Kang et al. 2007; Li et al. 2007).

The numerical experiments described so far in this section prescribe land conditions. Other experiments have also been performed allowing for two-way vegetation–climate interactions (i.e., land surface conditions are not specified but predicted). Using a simple dynamic vegetation model coupled with the Quasi-Equilibrium Tropical Circulation Model (QTCM), Zeng et al. (1999) showed that the best reproduction of the observed interannual precipitation variability over the Sahel during the past half century was obtained when interactions among vegetation, soil, and ocean components were all included. Wang et al. (2004) investigated the impact of large-scale oceanic forcing and local vegetation feedback on the variability of Sahel rainfall using a global biosphere–atmosphere model. When vegetation was dynamic, the model realistically reproduced the multidecadal-scale fluctuation of rainfall in the Sahel region. However, when the vegetation was kept static, the rainfall regime was characterized by fluctuations at much shorter time scales. This suggests that vegetation dynamics acts as a mechanism for the persistence of the regional climate. Kucharski et al. (2013) obtained a similar result and showed that about 60% of the observed Sahel drought could be reproduced if vegetation dynamics were included in their AGCM ensemble simulations, whereas only 30% could be reproduced if vegetation feedbacks were static. Furthermore, Kucharski et al. (2013) demonstrated that the dominant positive feedback mechanism for the vegetation impact on the Sahel drought is the albedo feedback, in accordance with early work by Charney (1975).

Although land use changes might not have been the main driver of the 1980s Sahel drought, their impacts over West Africa could increase on the coming years (Taylor et al. 2002). In fact, the work by Paeth et al. (2009) suggests that in climate change scenarios land use changes could become primarily responsible for the simulated climate response over West Africa.

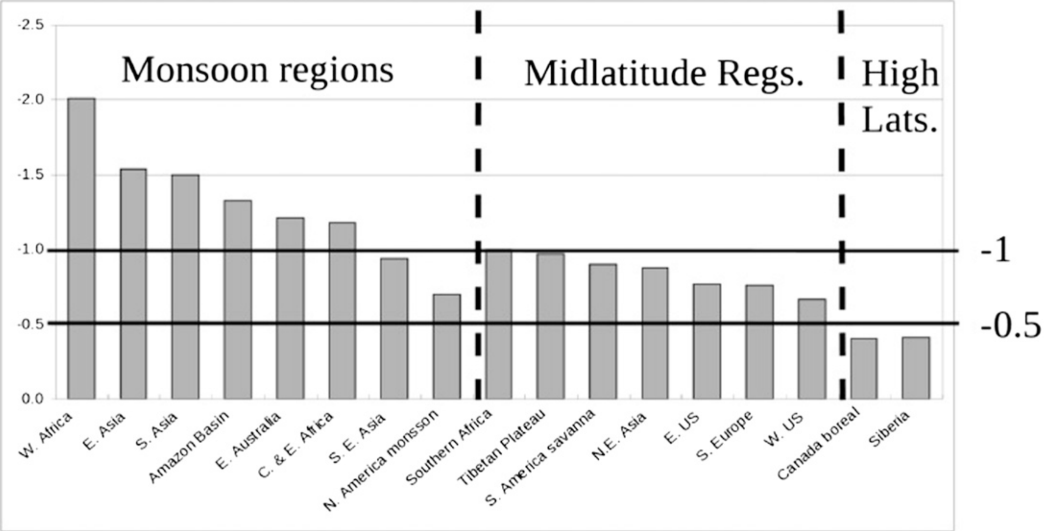

FIG. 8. Land surface: reductions of simulation error (mm day^{-1}) by introducing the VBP over different regions in different seasons [modified from Xue et al. (2010a)].

4. Seasonal forecasting of drought in Africa

During the last decade seasonal forecasting has matured from a research activity to a fully operational service, with many centers using initialized state-of-the-art coupled models. There are currently 12 WMO Global Producing Centers (GPCs) for long-range forecasting that routinely issue operational forecasts for rainy season totals (Graham et al. 2011). The forecasts are freely available for national meteorological services, regional climate centers, and global product centers via www.wmolc.org.

Over the African region, the skill of these long-range forecasting systems to predict seasonal total rainfall is high enough to make them useful for planning purposes. An example of the practical use of long-range forecasts and postprocessing techniques is the Prévisions Saisonnière en Afrique de l'Ouest (PRESAO; Fig. 9, top) forum, which meets annually to produce a consensus forecast for the West African region. To make this forecast, output from GPC dynamical systems and statistical models are combined and a spatial bias correction is made using canonical correlation analysis.

These improvements in forecasting seasonal averages have been achieved thanks to the continuous research completed in the last 10 years. For example, Philippon et al. (2010) found that the correlation between observations and a five-model ensemble mean from the ENSEMBLES Sixth Framework Programme (FP6) project (Hewitt 2004) was 0.55 for the Guinean rainfall variability mode. Batté and Déqué (2011) also used the ENSEMBLES dataset to analyze the skill of the multimodel system not only for the WAM but also the South African winter rainy season and the greater Horn of Africa long and short rains. They found that the multimodel ensemble improved the spread-to-skill ratio and average skill score over the use of a single model by as much as 10% when measured as potential economic value. Philippon et al. (2010) and Ndiaye et al. (2011) found that skill can be enhanced by predicting modes of variability using model output statistics (MOS) instead of using direct model output and therefore such enhancements are used to produce forecasts.

Despite these advances, there are still some remaining scientific questions such as large biases in tropical Atlantic SSTs in coupled models. Also, from a user's point of view, even more critical than the total seasonal rainfall is the ability to predict the temporal distribution of rain throughout the season (Salack et al. 2014), which determines the optimal planting and harvesting time (Marteau et al. 2011). This has created a clear demand for information such as the onset of rainy seasons in many parts of Africa (Ingram et al. 2002; Graham et al. 2011).

Vellinga et al. (2013) analyzed the links between SST and precipitation over the WAM region using dynamical forecasting systems from the ENSEMBLES project. Confirming the results found by Salack et al. (2014) in observations, Vellinga et al. (2013) showed that the forecast skill in coupled models was related to tropical Atlantic SSTs in June. The ability of models to forecast the timing of the monsoon onset was found to be useful, with relative operating characteristics (ROC) scores of 0.6–0.8 at 3-months lead time.

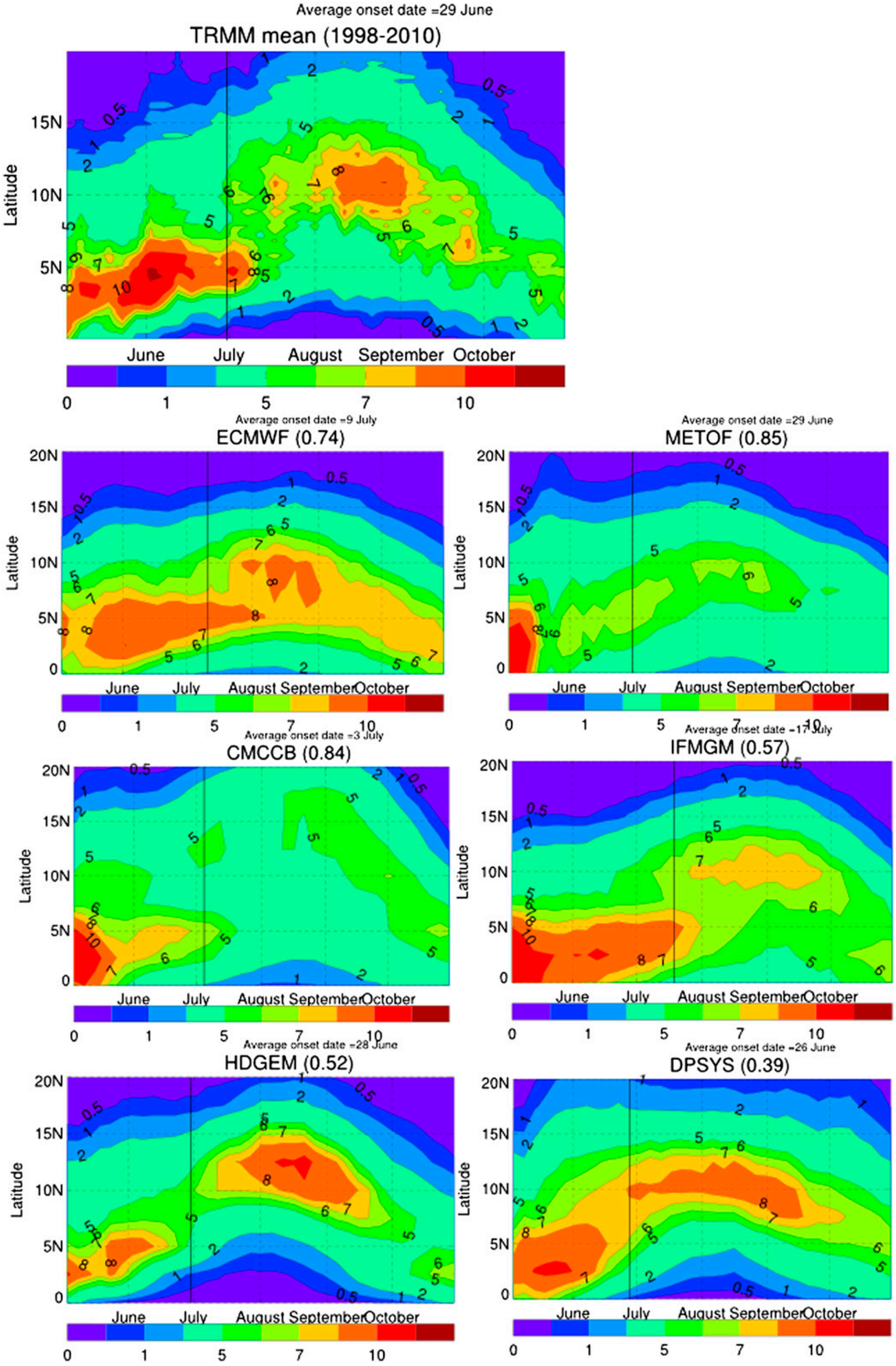

FIG. 9. Average time–latitude propagation of zonally averaged (10°W–10°E) rainfall over the West African monsoon region for observations and for six state-of-the-art coupled models from ENSEMBLES. The onset date for each model is shown as a vertical black line. For reference, the average onset date in observations is 29 June. [From Vellinga et al. (2013)]

A crucial point from the user perspective is that useful levels of skill are found even in some models with large mean rainfall biases over the region. This is important because, although there are still major model problems that need to be solved (such as biases in tropical Atlantic SSTs and total precipitation), the forecast systems are starting to be able to provide relevant probabilistic information to a crucial user question: Will the onset of the WAM be earlier or later than average this year? Figure 9 (from Vellinga et al. 2013) shows a major advance toward a meaningful answer to such a question, since only 10 years ago there was no forecasting system able to do it with a direct and relevant application to users.

5. Decadal prediction of the WAM

The new field of decadal climate prediction aims to provide climate information on time scales from a few years to a few decades into the future, which is recognized as a key planning horizon (Goddard et al. 2010; Vera et al. 2010; Smith et al. 2012). Decadal predictions are certainly of increasing scientific interest because they potentially represent a benefit to society through improvements in the development of climate services and adaptation strategies. They are recognized as a major part of the CMIP5 experimental design (Taylor et al. 2012).

Decadal predictions explore the benefits of initializing climate models. The initialization tries to provide the forecast system with contemporaneous information on, for instance, the state of the upper-ocean heat content, to achieve forecast quality beyond that provided by simulations based only on externally forced signals such as the standard CMIP3 and CMIP5 climate change scenario experiments. The objectives of decadal prediction include capturing low-frequency internal variability and correcting the model response to climate change forcings and commitment (Meehl et al. 2009, 2014; Murphy et al. 2010; Goddard et al. 2013; Doblas-Reyes et al. 2013).

As has been indicated in previous sections, WAM variability at decadal time scales results from a combination of internal and externally forced components (Biasutti 2011; Mohino et al. 2011a), including anthropogenic aerosols (e.g., Biasutti and Giannini 2006) and greenhouse gases (e.g., Biasutti et al. 2008). All the evidence points to the WAM as a good test bed for assessing the feasibility of decadal prediction.

Using the first coordinated experiment to explore the feasibility of decadal prediction (ENSEMBLES; Doblas-Reyes et al. 2010), van Oldenborgh et al. (2012) and MacLeod et al. (2012) found no significant skill in point-wise precipitation predictions over West Africa for 4-yr forecast averages. Predictions of precipitation trends did not have skill either. MacLeod et al. (2012) further suggested that the spread of precipitation hindcasts over land is such that the potential for predictability may not be sufficient to be useful. However, García-Serrano et al. (2013) have shown that the ENSEMBLES forecast systems are reliable, in a probabilistic sense, when recapturing the Sahelian precipitation variability. Instead, multiyear forecast quality assessment of the dominant WAM precipitation regimes suggests that the Guinean rainfall is not skillful.

From the most recent generation of climate models (i.e., CMIP5), Goddard et al. (2013), Gaetani and Mohino (2013), and Doblas-Reyes et al. (2013) found positive pointwise precipitation correlation over West Africa. However, this finding is model dependent, and the conditional biases that exist in the predictions may actually make the information less accurate than climatological averages (Goddard et al. 2013). A proper simulation of the remote SST influences on the Sahel appears to be key for predictability at decadal–multidecadal time scales (Martin and Thorncroft 2014b). The Sahelian rainfall skill is likely associated with a significant skill in the AMO prediction (García-Serrano et al. 2015; Guemas et al. 2015), although the relative SST difference between the subtropical North Atlantic and the tropics (Giannini et al. 2013) and SST variability in the Mediterranean Sea (e.g., Fontaine et al. 2010) have also been shown to be important for providing skill (Martin and Thorncroft 2014b). Results from CMIP5 (Goddard et al. 2013; Gaetani and Mohino 2013) show a nonnegligible contribution to the Sahelian rainfall skill from the external radiative forcing (Fig. 10), whereas initialized hindcasts outperform empirical predictions based on persistence at longer lead times (Gaetani and Mohino 2013; Martin et al. 2014).

The good performance of the ENSEMBLES (García-Serrano et al. 2013) and CMIP5 (Gaetani and Mohino 2013) decadal forecast systems in reproducing the relationship between the Sahel precipitation and its associated SST patterns encourages the promotion of improved decadal prediction systems in the future where the problems of SST biases are properly dealt with. This is only achievable in a context of a model development strategy across all communities that use climate models, as suggested by the WCRP.

6. Future projections

Following the IPCC AR4, several studies were published on twenty-first-century rainfall scenarios over West Africa. The successful simulation of the Sahel rainfall requires the capture of several physical mechanisms with

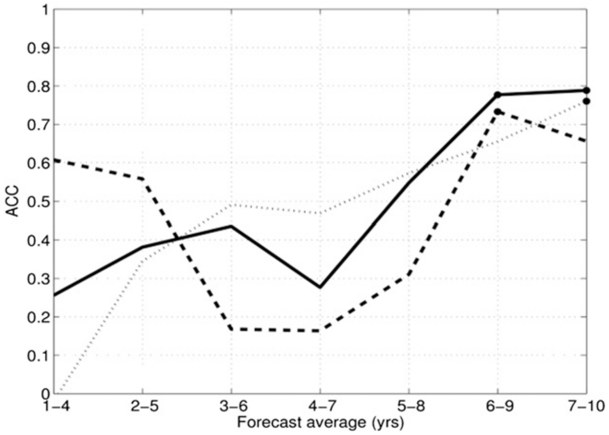

FIG. 10. Decadal prediction: anomaly correlation coefficient (ACC) between the Sahelian precipitation index (10°–20°N, 15°W–15°E) from the CRU dataset and decadal hindcasts (solid), historical experiments (dashed), and decadal-forcing residuals (dotted). ACC is computed for the multimodel ensemble mean. Dots indicate the 95% significant positive correlations; significance is estimated using a Monte Carlo test with 200 permutations. The decadal-forcing residuals are analyzed to obtain an evaluation of the initialization weight in the decadal experiments [see Gaetani and Mohino (2013) for details].

contributions that may have opposite signs (Druyan 2011). The differential heating of land and ocean can strengthen the heat low in the Sahara and enhance the monsoon flow and thus rainfall (Haarsma et al. 2005; Biasutti and Sobel 2009). Even in the absence of circulation changes, the warming-induced increase in atmospheric temperature would enhance precipitation in regions of moisture convergence such as the Sahel at the peak of the monsoon (Held and Soden 2006; Seth et al. 2011). At the same time, warming could lead to increased stability and localized subsidence, in the future just as in the past (Held et al. 2005; Seth et al. 2011). All these processes are likely to be relevant, but their influences may differ for different regions in North Africa, different times within the rainy season and, unfortunately, across different models (see, e.g., Giannini 2010).

Projections of summertime Sahel rainfall at the end of the twenty-first century by the CGCMs in CMIP3 and CMIP5 of the IPCC are shown in Figs. 11a and 11b for the emission scenarios SRES A1B and RCP4.5, respectively. Although the spread in rainfall projections is large at the end of the twenty-first century over the Sahel within both multimodel ensembles, there is evidence for a general tendency for slightly wetter conditions over central Sahel and drier conditions over Senegal, Mauritania, and southern Mali. A meridional dipole pattern of rainfall anomalies is also observed over the tropical Atlantic consisting of drier conditions over the Gulf of Guinea and wetter conditions north of 5°N. The multimodel agreement is better for the CMIP5 (Fig. 11b) than for the CMIP3 ensemble (Fig. 11a), and the results are more significant when the approach ‘‘one model, one vote’’ is used (Monerie et al. 2013).

Another recent study of Roehrig et al. (2013) analyzes CMIP5 simulations along a range of time scales from interannual to decadal and future projections. CMIP5 climate change projections in surface air temperature and precipitation are found to be very similar to those obtained in CMIP3. Their results highlight a robust warming trend over the Sahel and an increase in rainfall in the eastern and a decrease in the western Sahel. However, there is a spread between models because of the deficiencies in simulating the Atlantic variability. In most of the models there is a systematic southward shift of the ITCZ.

The CMIP5 simulations reaffirm and strengthen the CMIP3 projections for changes in the seasonal cycle of Sahel rainfall (see, e.g., Biasutti and Sobel 2009; Biasutti 2013). A delay is projected on the start of the rainy season in the future throughout the Sahel, and especially over West Africa; instead, more abundant precipitation in the late rainy season is projected. There is robust agreement on the seasonality changes and the distinction between West Africa and the central Sahel in both CMIP3 and CMIP5. The projected increase in peak rainfall is consistent with a global pattern of enhanced seasonality of tropical rainfall (Chou and Lan 2012; Chou et al. 2013). The drying at the onset of the rainy season might instead be a manifestation of the drying of the convective margins (Neelin et al. 2003; Seth et al. 2011, 2013).

Greenhouse gas (GHG) increases affect Sahel rainfall not only via the warming of global SST (slow response), but also via its direct effect on the temperature and energy fluxes of the land–atmosphere system (fast response; Patricola and Cook 2011; Giannini 2010). Using idealized CMIP5 simulations, Biasutti (2013) found that throughout the rainy season the slow response leads to less rain across the Sahel while the fast response forces wet anomalies that span the entire Sahel, although they are stronger in the east. Nevertheless, the fully coupled response, especially the change in seasonality, cannot be explained in terms of a simple linear superposition of the individual fast and slow responses. Biasutti (2013) speculates that the different phasing of the annual cycle over land and ocean interact to determine the projected delay of the Sahel rains in the coupled response.

Another proxy for drought in climate projections can be obtained by counting the annual number of dry days, which are defined as those when daily rainfall is less than 1 mm (Frich et al. 2002; Vizy and Cook 2012). Vizy et al. (2013) indicate that current models underestimate the

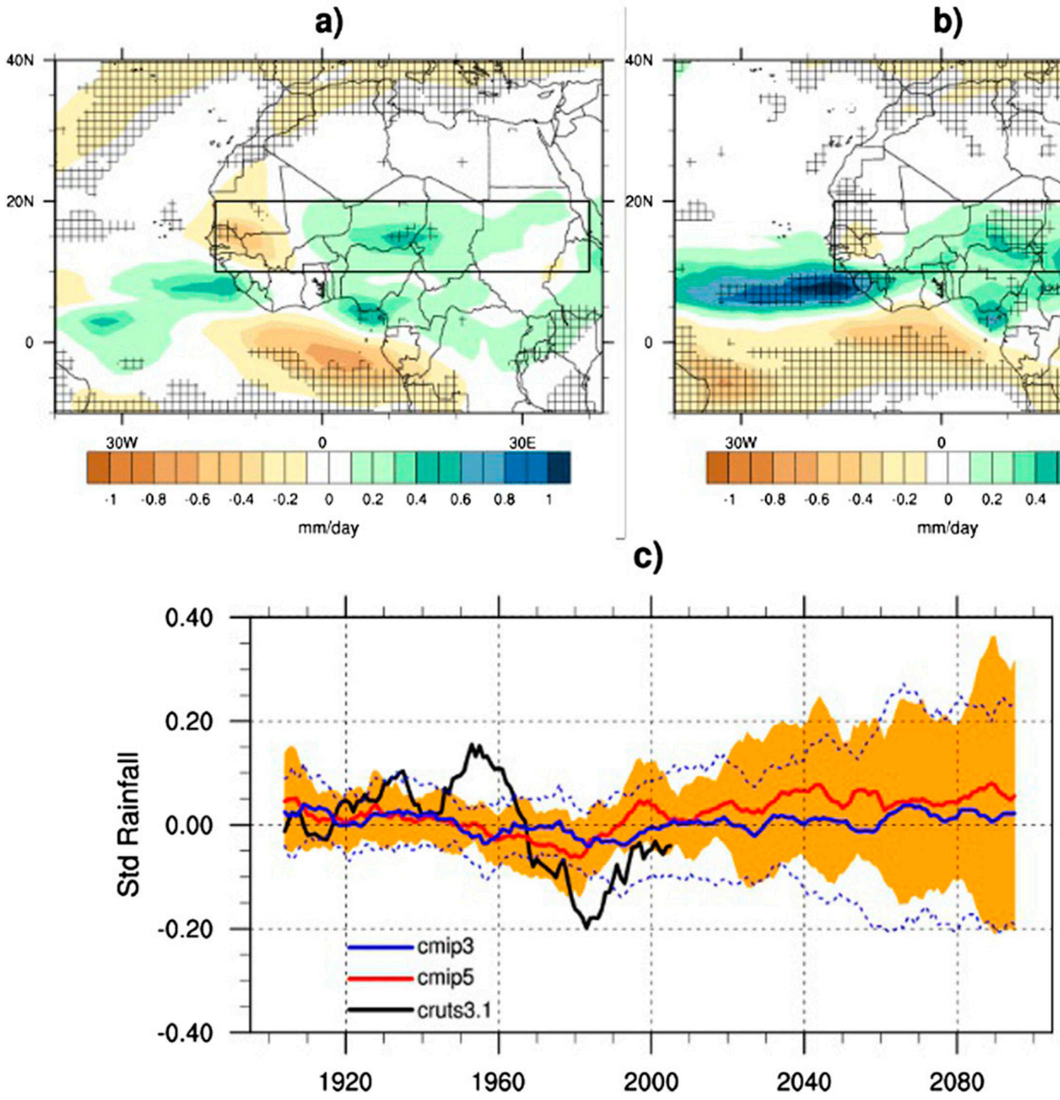

FIG. 11. Future projections: summer (JAS) rainfall changes (mm day^{-1}) as simulated by the (a) CMIP3 and (b) CMIP5 multimodel ensemble means. Changes are calculated between the SRES A1B scenario and historical experiments for CMIP3 and the RCP4.5 scenario and the historical experiments for CMIP5 (2065–95 vs 1970–99). The stippling indicates grid boxes where 50% of the models simulate either positive or negative changes. (c) JAS Sahel rainfall indices for the CMIP3 and CMIP5 multimodel ensembles and the CRU TS3.1 observations (see the box for the domain). The time series are in units of mean JAS rainfall where the mean is calculated for the period 1901–99. The one standard deviation spread is shown by the orange envelope for the CMIP5 ensemble and by the blue dotted lines for the CMIP3 ensemble. All indices have been low-pass filtered using an 8-yr running average [modified from Biasutti (2013)].

number of dry days along the Guinean coast and over the Congo basin, but conclude, on the basis of intermodel agreement and consistency across time periods, that there is a strong likelihood for fewer dry days over the Sahel of eastern Mali, Niger, Nigeria, and Chad and more dry days over Senegal and the far western Sahel. There is less agreement about how the number of dry days per year will change along the Guinean coast. These results are consistent with the seasonal mean changes discussed above but need to be reconciled with the expectations of Giannini et al. (2013), who showed that Sahel rainfall recovery results from increases in mean daily accumulation rather than in frequency.

7. Summary, remaining questions, and future directions

The Sahel experienced starting in the 1970s one of the most dramatic droughts in the historical record, with consequences that have affected large areas and

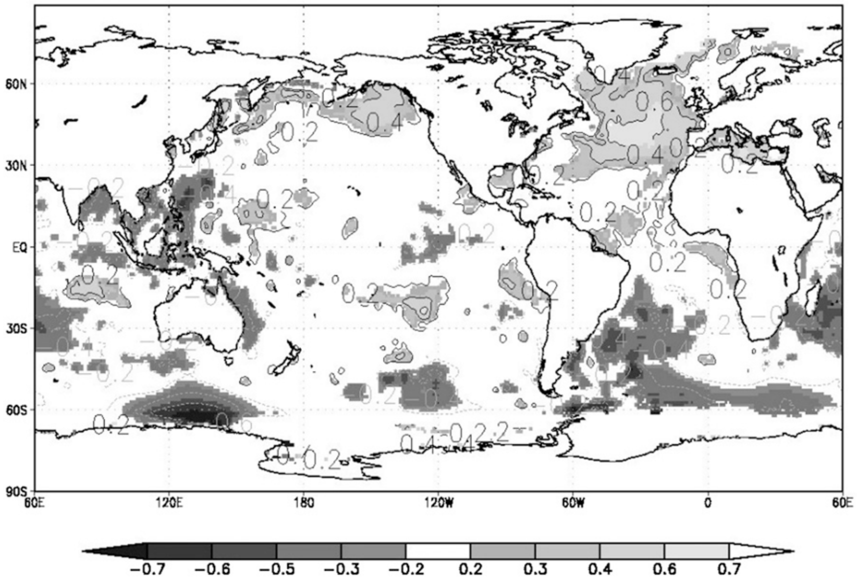

FIG. 12. Projection of the anomalous SSTs onto the grey bottom correlation line in Fig. 6. Only 95% significant regions under a Monte Carlo test are represented.

populations. The present paper reviewed studies on Sahel rainfall variability at time scales from interannual to decadal. The emphasis has been on the role of the oceanic anomalies, because according to the consensus view these are the most important contributors to rainfall variability in West Africa at the time scales of interest. Nevertheless, the influence of the land surface processes was also included as they are important contributors the West Africa rainfall variability. Future projections were also mentioned.

a. *Summary*

1) INTERANNUAL VARIABILITY

In interannual time scales, a warming of the equatorial Atlantic and Pacific/Indian Oceans results in rainfall reduction over the Sahel. On the contrary, positive SST anomalies over the Mediterranean Sea tend to be associated with increased rainfall.

A dependence on time (nonstationarity) of these relationships has been found by recent studies (Joly and Voldoire 2009; Rodríguez-Fonseca et al. 2011; Mohino et al. 2011b; Losada et al. 2012). Before the 1970s positive SST anomalies over the Gulf of Guinea (Atlantic Niños) were associated with a dipole pattern of precipitation anomalies consisting of positive values along the coast of Guinea and negative ones over the Sahel (Fig. 6). After the 1970s, a similar pattern of SST anomalies in the Gulf of Guinea appears to have local impacts but no significant remote impacts over the Sahel as SST anomalies in the Pacific seem to increase their influence in this region. Also the influence of SST anomalies in the Mediterranean Sea has increased in the last decades.

Current AGCMs generally capture these features. It has been argued that this time dependence is due to the changing configuration of tropical SST anomalies in different adjacent tropical oceans, which can interact either constructively or destructively according to time (Losada et al. 2012). Figure 12 shows that the periods for which the Atlantic and Pacific may both strongly influence Sahelian rainfall present a multidecadal anomalous SST pattern resembling the positive and negative phases of the Atlantic multidecadal oscillation (AMO), respectively. Thus, a warmer or cooler climatological SSTs in the equatorial and tropical South Atlantic could play an active role.

In addition to SST variability, volcanic eruptions may influence the WAM rainfall some years (Haywood et al. 2013),

2) INTERDECADAL VARIABILITY

SST variability at decadal time scales provides the most important influence leading to drought over the Sahel. It has been shown that the global warming trend, positive phase of the interdecadal Pacific oscillation, and negative phase of the AMO lead to reductions in Sahel precipitation. State-of-the art CGCMs are able to reproduce the observed drying trend over the Sahel. However, models fail in obtaining the observed amplitude and neither generation of CMIP climate models reproduces the magnitude of the observed rainfall variability at decadal to multidecadal time scales over the twentieth century.

Observational evidence also indicates a strong decadal climate component in the Sahel and surrounding areas from the 1950s to the 2000s in vegetation cover and land use/land cover (LULC) change, as well as in aerosol types and spatial distributions (e.g., Rowell 2003; Xue et al. 2004a,b; Lau and Kim 2007; Hastenrath and Polzin 2011). Vegetation dynamics, in particular, may contribute to the persistence of anomalies of the regional climate.

3) MECHANISMS FOR SST IMPACT

The mechanisms for SST impact operating at different climate scales, from interannual to decadal, are conceptually similar: the Atlantic interhemispheric gradients are related to changes in the position of the ITCZ and the warming of the Pacific tropical SSTs is related to anomalous equatorial atmospheric Rossby waves enhancing the subsidence over the Sahel.

A cooling in the equatorial Atlantic influences the large-scale dynamics, enhancing the meridional gradient in sea level pressure and strengthening the monsoon, while warming of the southern tropical Atlantic enhances the anomalous divergence over the Gulf of Guinea and the dipolar configuration of anomalous rainfall over Sahel. Anomalous Mediterranean Sea warm events are associated to a more intense monsoon with enhanced moisture convergence over the Sahel, which is advected by the climatological northerly flow. Moreover, an anomalous warming in the Pacific and Indian Oceans leads to reduced Sahel rainfall through an anomalous subsidence over the Sahel in association with an equatorial Rossby atmospheric wave.

4) FUTURE PROJECTIONS

The agreement among future projections has improved from CMIP3 to CMIP5. Although rainfall projections for the Sahel have a large spread at the end of the twenty-first century, model projections exhibit a general tendency for slightly wetter conditions over central part and drier conditions over the western part. A meridional dipole pattern of rainfall anomalies is also obtained over the tropical Atlantic consisting of drier conditions over the Gulf of Guinea and wetter conditions north of 5°N. According to the projections, the start of the rainy season (onset) will be delayed in the future throughout the Sahel and especially over West Africa, with more abundant precipitation simulated during the late rainy season.

5) FORECASTING

The skill of numerical forecasts has improved during the last decades. The increased attention to dynamical vegetation schemes has contributed to improvement. Prediction systems have evolved from seasonal to decadal forecasting. Current forecast systems show skill in their seasonal predictions of total rainfall amounts over West Africa, although this is generally limited to the Gulf of Guinea. Skill is improved when using multimodel predictions rather than single model ones. However, for harvesting purposes the timing of the rainy season is even more relevant than total rainfall amounts. Because of this, the seasonal forecasting community has lately focused on providing information beyond seasonal rainfall. Recent works show that there is useful skill to forecast the onset of the monsoon and that this skill can be related to SST anomalies in the tropical Atlantic in June. Moreover, the relevance of making actionable information available with a lead time of several years is recognized as a key planning horizon, making decadal prediction a new challenge for the scientific community. Significant correlation with the observations is found in some decadal predictions when simulating the relationship between the dominant WAM rainfall modes and their associated SST patterns, suggesting a potential for skillful decadal predictions in the future.

b. Numerical modeling issues

Significant shortcomings remain in the ability of numerical models to simulate some outstanding aspects of the tropical Atlantic climate and its variability.

- Most contemporary coupled atmosphere–ocean (CGCMs) have important rainfall, wind, and SST biases in the tropical Atlantic. The simulations show too weak trade winds, a spurious ITCZ south of the equator, and too warm eastern tropical SSTs, compromising the successful representation of WAM and its response to tropical Atlantic variability.
- CGCMs have difficulties in capturing the relationships among Pacific SSTs and WAM rainfall anomalies during the developing phase of an El Niño (La Niña) event.
- There are large differences among models in the intensity and variance of simulated precipitation and the majority of CGCMs fail to produce proper intensities of the African easterly jet and the tropical easterly jet.
- RCMs capture the northward jump of the precipitation band that represents the monsoon onset over Sahelian Africa, which GCMs fail to simulate. However, the jump in the RCMs occurs earlier than observed, suggesting serious model limitations for predicting the timing of monsoon onset.
- It is very important to emphasize that over West Africa, RCMs will not necessarily provide better

results than GCMs because both modeling systems show a number of similar biases that are still unresolved. The impact community, in particular, must exercise caution in the interpretation of results from impact models forced by GCM and/or RCM models. At this point in time, such an exercise should be considered more as a scientific enquiry than an operational forecast.

- Since forecasts are sensitive to the quality of the data used to initialize the model, an improvement of the initial conditions used over the equatorial and extratropical Atlantic as well as over land is just as essential to improve the forecast quality as the model improvement is.

c. *Remaining questions*

- The role of the Indian Ocean in forcing interannual rainfall anomalies over West Africa is not clear as some papers have reached contradictory conclusions.
- The reasons for the nonstationary impact of tropical SST anomalies in different basins are not clear at the present time. There are at two competing hypotheses that require further validation: statistical artifacts due to sampling errors and modulations by changes in the ocean climatology, which introduce nonlinearities in the system and, thus, different impacts.
- Despite the general agreement that the long-term Sahel drought was mainly driven by SST variability and amplified by land surface processes, the details as to which basin or SST pattern lead this drought are still debated. Some works suggest that the warming of the tropical SSTs in the Indian, Pacific, and/or Atlantic Ocean basins were the dominant factors, while others place a more fundamental role on the interhemispheric north–south SST gradient in the Atlantic.
- Another key point still under debate is the attribution of the long-term Sahel drought to anthropogenic factors, as greenhouse gases or anthropogenic aerosols. On the one hand, some works suggest that these factors played little or no role in the twentieth-century Sahel drought. On the other hand, other studies argue they were the main driver of the drought.
- There is still a substantial spread in rainfall projections, which is large at the end of the twenty-first century over the Sahel.
- What are the key model components to be improved for a higher skill of drought prediction over the Sahel? Should radiative impacts of natural aerosols from the continent be considered in reference to the systematic errors of CGCMs over the Atlantic, both in the subtropics and the tropics? The answers to these questions may require the realization of field campaigns in the eastern tropical Atlantic.
- Could land surface processes become the primarily responsible for drought over West Africa in change scenarios?

d. *Future directions*

One of the most dramatic and immediate impacts of climate variation is on disease, especially the vector-borne diseases that disproportionally affect the poorest populations in West Africa (Hoshen and Morse 2004; Caminade et al. 2011). To assist with their short-term management and make projections of their future likely impacts, the project Quantifying Weather and Climate Impacts on Health in Developing Countries (QWECI) has developed and tested the methods and technology required for an integrated decision support framework for the quantification and prediction of climate and weather on health impacts in Africa. In particular, while there is useful skill in reproducing global and regional temperatures (Doblas-Reyes et al. 2013; Guemas et al. 2015), the reduced skill in forecasting WAM rainfall anomalies (Doblas-Reyes et al. 2013) prevents its use in driving health-impact models (which also require rainfall estimates) on decadal time scales (MacLeod et al. 2012).

New European projects are being launched to enhance predictability of this region. For example, the Seasonal-to-Decadal Climate Prediction for the Improvement of European Climate Services (SPECS) EU project (http://www.specs-fp7.eu/), which started in 2012, produces quasi-operational and actionable local climate information at seasonal-to-decadal time scales over the longest possible observational period over land, focusing on Europe, Africa, and South America. The aim is to provide information with improved forecast quality, focusing on extreme climate events to enhanced communication and services for wide range of public and private stakeholders. Also, EU project Enhancing Prediction of Tropical Atlantic Climate and Its Impacts (PREFACE), which started in November 2013, aims to reduce uncertainties in our knowledge of the tropical Atlantic climate, improving climate prediction and the quantification of climate change impacts in the region. In turn, the recently launched EU Dynamics–Aerosol–Chemistry–Cloud Interactions in West Africa (DACCIWA) project, which started in December 2013, aims at improving our understanding of interactions between emissions, clouds, radiation, precipitation, and regional circulation over West Africa, which will reduce model uncertainties in climate predictions over the area. The observational datasets, acquired within AMMA and more recent programs such as Fennec (Washington et al. 2012) are the backbone of modern research efforts.

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