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ADVANCED REVIEW

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# Rainfall trends in the African Sahel: Characteristics, processes, and causes

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**Abstract**

Sahel rainfall is dynamically linked to the global Hadley cell and to the regional monsoon circulation. It is therefore susceptible to forcings from remote oceans and regional land alike. Warming of the oceans enhances the stability of the tropical atmosphere and weakens deep ascent in the Hadley circulation. Warming of the Sahara and of the nearby oceans changes the structure and position of the regional shallow circulation and allows more of the intense convective systems that determine seasonal rain accumulation. These processes can explain the observed interannual to multidecadal variability. Sea surface temperature anomalies were the dominant forcing of the drought of the 1970s and 1980s. In most recent decades, seasonal rainfall amounts have partially recovered, but rainy season characteristics have changed: rainfall is more intense and intermittent and wetting is concentrated in the late rainy season and away from the west coast. Similar subseasonal and subregional differences in rainfall trends characterize the simulated response to increased greenhouse gases, suggesting an anthropogenic influence. While uncertainty in future projections remains, confidence in them is encouraged by the recognition that seasonal mean rainfall depends on large-scale drivers of atmospheric circulations that are well resolved by current climate models. Nevertheless, observational and modeling efforts are needed to provide more refined projections of rainfall changes, expanding beyond total accumulation to metrics of intraseasonal characteristics and risk of extreme events, and coordination between climate scientists and stakeholders is needed to generate relevant information that is useful even under deep uncertainty.

This article is categorized under:

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**KEYWORDS**

climate change, drought, monsoon, sahel

## 1 | INTRODUCTION

The name Sahel refers to the semi-arid region stretching longitudinally from Senegal in West Africa to Sudan and Ethiopia in East Africa and latitudinally from just north of the tropical forests to just south of the Sahara desert (roughly between 10° and

20°N). Across this vast expanse, seasonal rainfall varies sharply in the meridional direction but much less in the zonal direction (Figure 1a). The climatology is well described by the meridional movement of a zonal rain band whose summertime northward progression produces a single rainy season: ramping up around May, winding down by October, and with the bulk of the annual rainfall falling between June and September (Figure 1b). Annual mean rainfall decreases from more than 800 mm in the south to less than 200 mm in the north and determines the progression of natural land cover from shrublands to grasslands and savanna, and the prevalence of sedentary agriculture or nomadic pastoralism. Across the region, abundance or scarcity of rainfall—as well as its distribution over the rainy season and the associated maximum temperature extremes—determines the success or failure of smallholder farming systems, which are often rain-fed. At the same time, extreme rainfall events cause urban floods, impair drinking water distribution systems, and erode top-soil from the land. There is, therefore, a strong need for monitoring and predicting rainfall changes throughout a large range of spatial and temporal scales, from local weather to continental climate change.

In the remote (Shanahan et al., 2009) and recent (Nicholson, Fink, & Funk, 2018) past, rainfall in the Sahel has undergone profound changes and more changes of the same magnitude are expected for the near future (Chadwick, Good, Martin, & Rowell, 2016). This review aims to assess how well we understand the causes of past variability and how confident we are in our ability to predict the future. Confidence in model projections cannot rely on past model performance alone. Instead, it requires that our predictive models represent all relevant mechanisms for Sahel rainfall: those that controlled its variability in the past, and those that will control its trends in a future fundamentally altered by anthropogenic emissions. Thus, we determine our reasons for confidence—or lack thereof—by reviewing past and projected changes in Sahel rainfall through the lenses of climate dynamics. This means that (a) we focus on the mechanisms of rainfall variations at different scales, (b) we assess models on their ability to reproduce those mechanisms, and (c) we assess climate projections on the likelihood that the same mechanisms will be relevant in future decades.

We limit our review to the regional and continental trends in seasonal accumulation, the timing of the rainy season, and the mean intensity of daily rainfall. Changes in other aspects of Sahelian hydro-climate can be just as important for their impact on natural and human systems: consider, for example, the hydrological impacts of subdaily rainfall intensity, or the hazard posed by extreme dry or wet spells for agriculture and land degradation. Yet, this review skirts the investigation of these hydro-climatic variables. Our choice is motivated by the desire to assess trends in quantities that are

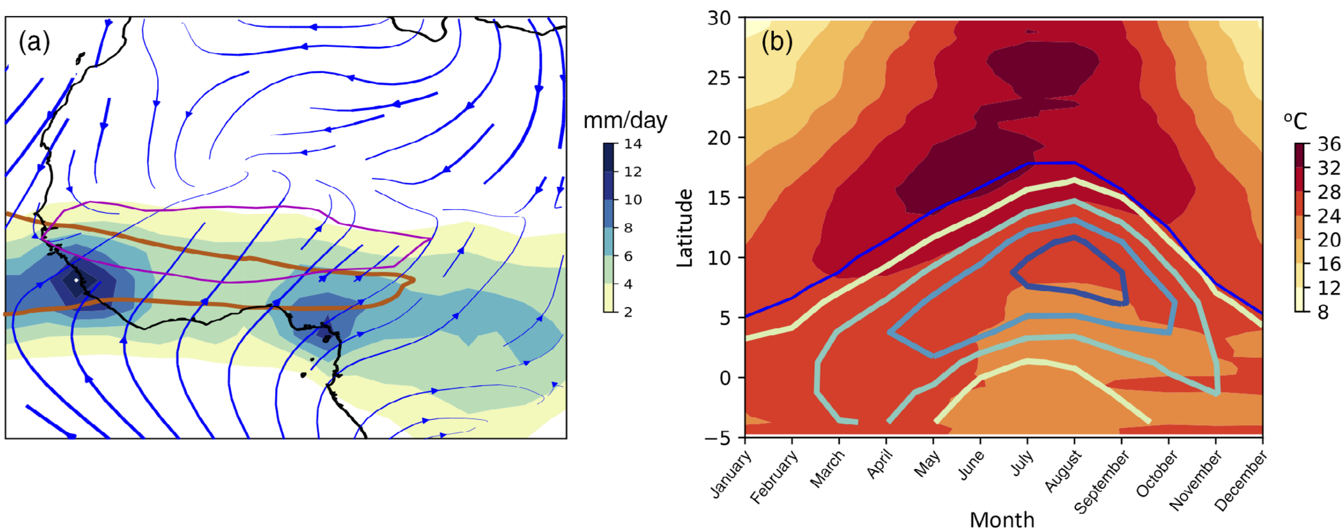


**FIGURE 1** The main features of the rainfall climatology in West Africa. (a) Mean May–October rainfall (color shading); location of the African Easterly Jet (AEJ, magenta contour) as indicated by the 9 m/s contour of the easterly wind at 600 hPa; maximum African Easterly Waves (AEW, orange color; contour retraced from Figure 5a in Thorncroft & Hodges, 2001) as indicated by the a track density scaled to number density per unit area ($10^6$ km$^2$) per season (MJJASO) greater than 6; and near surface (925 hPa) wind (streamlines; ERA40, Uppala et al., 2006). All fields are for the 1979–1998 period, for consistency with Thorncroft and Hodges (2001). (b) The seasonal cycle of sector mean (20°W-30°E) surface air temperature (warm shaded colors; CPC Monthly Global Surface Air Temperature, Fan & van den Dool, 2008), precipitation (contours, same colors as in (a); GPCP Huffman et al., 1997), and the intertropical discontinuity (ITD, indicated in blue by the zero contour of the 925 hPa meridional wind from ERA40 reanalysis). Note how the advance of the ITD is connected with the warming of the Sahara and how the rain band stays to the south of the ITD

reasonably well observed and for which current-generation climate models are most reliable. Efforts to quantitatively predict higher-order aspects of the precipitation statistics over Africa are coming online but are still in their infancy. This is due to the inability of global coupled models to resolve the relevant dynamics, to the relative few attempts at climate projections using convection-permitting models, and to the scarcity of long-term observations that could constrain statistical models.

This review is organized as follows. In Section 1 we survey the drivers of rainfall variability that are relevant for the Sahel. In Section 2 we summarize observations of rainfall variability in the 20th century. We focus on the drought decades (the 1970s and 1980s) and on the dominant influence of SST on seasonal mean anomalies. In Section 3 we zoom in on the most recent decades and review trends in the rainfall distribution across the rainy season. We relate such trends to the dynamics of intense rainfall events and to the influences of external drivers on storm environments. In Section 4 we connect past and current trends to changing anthropogenic forcings: emissions of aerosols and greenhouse gases (GHGs) and land-use changes. In Section 5 we suggest how our understanding of mechanisms of Sahel rainfall variability can inform our assessment of future projections. We appraise the reliability of consensus projections in view of systematic model biases and simplifications; we emphasize remaining uncertainty; and suggest how knowledge of mechanisms of regional variability can help paint plausible regional scenarios for decision making. Section 6 concludes by providing an outlook on the creation and use of climate information for the Sahel.

## 2 | A ZOOMING PERSPECTIVE ON SAHEL RAINFALL

Variability in Sahel rainfall is inextricably connected with the variability of the atmospheric circulation. We can think of ascent in the African rain band as a facet of the planetary Hadley circulation, which exports energy from regions of net energy input (the warm tropics) to regions of net energy output (the higher latitudes) (Biasutti et al., 2018). According to this perspective, Sahel rainfall variations are governed by global-scale constraints.

Yet, the seasonal accumulation of rainfall across the Sahel is the aggregate of weather features that are, in comparison, short-lived (a few hours) and small-scale (a few 100s km in diameter). Specifically, 70–90% of the annual precipitation (the smaller percentage in the southern–Sudanian–zone) in West Africa is produced by Mesoscale Convective Systems (MCSs): fast-moving squall lines and larger Mesoscale Convective Complexes (Fink, Vincent, & Ermert, 2006; Mathon, Laurent, & Lebel, 2002). For this reason, the same continental-scale variability that has been explained through planetary-scale constraints also ought to be explained in terms of what controls the triggering and growth of storms. This leads to a more regional perspective, one that emphasizes the dynamical features controlling wind shear and moisture, which are key environmental variables for the development of mesoscale storms (Houze, 2004).

Explaining the mechanisms of variability of Sahel rainfall, thus, might require that we emphasize aspects of the system that range from the planetary to the mesoscale. We review these complementary perspectives here and we refer to them in our discussion of trends.

### 2.1 | The ITCZ

The dominant mode of ITCZ[1] variability for seasonal to multidecadal time scales, namely its meridional shift, can be explained considering the role of atmospheric circulation in the planetary energy budget. The Hadley cell transports moisture into the ITCZ in its lower branch and transports energy away from the ITCZ in its upper branch (see the faded circulation depicted in Figure 2a). In the mean, the ITCZ is just north of the equator, with the net result that energy is moved from the Northern Hemisphere (NH) into the Southern Hemisphere (SH) (Marshall, Donohoe, Ferreira, & McGee, 2014). If the NH experiences anomalous heating, the atmosphere partially compensates by rearranging the circulation so that there is enhanced transport of heat *away* from the NH. For this to happen, more moisture needs to be transported *into* the NH and the ITCZ must shift to the north (see schematic in Figure 2a; for a detailed derivation see Kang, Held, Frierson, and Zhao (2008); Kang, Frierson, and Held (2009); Donohoe et al. (2013) and following reviews: Schneider et al. (2014); Biasutti et al. [2018]; Kang et al. (2018)).

This mechanism is broadly consistent with a view that emphasizes surface temperature changes (Chiang, Biasutti, & Battisti, 2003; Folland, Palmer, & Parker, 1986). Figure 2b shows that the inter-hemispheric SST gradients have co-varied with Sahel rainfall at decadal and multidecadal time scales in the observational record, indicating that the Sahel responds to remote forcings in a way consistent with the energetic framework for the ITCZ (Hwang, Frierson, & Kang, 2013; Schneider et al., 2014): the Sahel receives abundant rainfall when the ITCZ is shifted anomalously north during summer, and is in

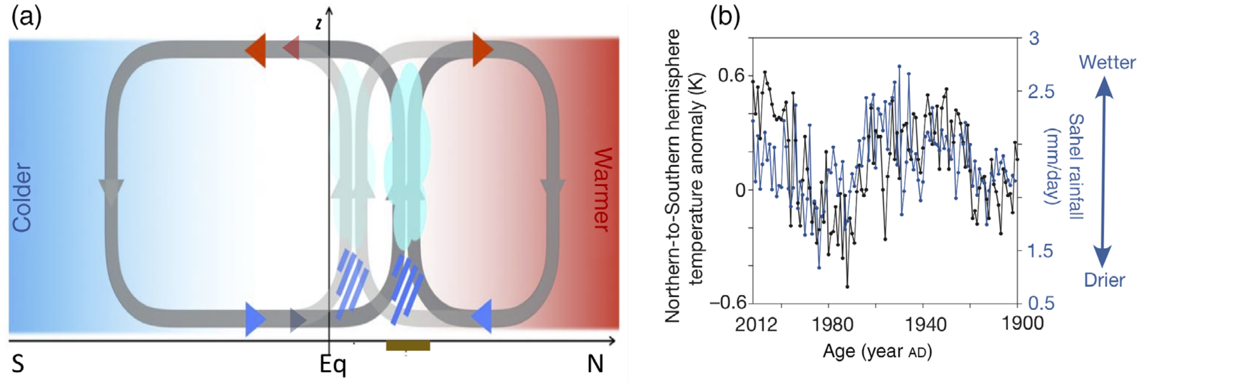


**FIGURE 2** (a) Schematic that describes how inter-hemispheric extratropical thermal forcing is balanced by the adjustment of the Hadley circulation. Suppose the northern (southern) extratropics are warmed (cooled). The faded (dark) gray contours in the upper panel indicate the Hadley circulation in the reference (perturbed) state. The Hadley circulation transports moisture equatorward following its lower branch (blue arrow) and transports energy poleward following its upper branch (red arrow). (Reprinted with permission from Kang, Shin, and Xie (2018). Copyright 2018 Nature; under the creative commons license http://creativecommons.org/licenses/by/4.0/). (b) Temperature contrast between Northern and Southern hemisphere extratropics (poleward of 24°N and 24°S) based on instrumental data (black), and average daily rainfall over the Sahel (12°−18°N, 20°W–35°E) during June–October based on land station data (blue). All temperatures and temperature contrasts are given as anomalies relative to the 1960–1991 AD mean (Reprinted from Schneider, Bischoff, and Haug (2014). Copyright 2014 Springer-Nature)

drought when the ITCZ stays closer to the equator. The link to the ITCZ remains a key tool in understanding the Sahel response to extratropical and global-scale forcings such as increasing greenhouse gas concentration (Biasutti & Sobel, 2009; Song, Leung, Lu, & Dong, 2018), anthropogenic aerosols (Hwang et al., 2013), volcanic eruptions (Haywood, Jones, Bellouin, & Stephenson, 2013), land use (Swann, Fung, Liu, & Chiang, 2014), and dust (Yoshioka et al., 2007).

## 2.2 | The regional convective center

To explain tropical influences on Sahel rainfall variability, it is useful to emphasize that the Sahel is a zonally-confined rainy region, that is, to emphasize the distinction from the ITCZ without necessarily emphasizing the specific geography of the region. The essential process is that strong convection is happening elsewhere in the tropics and the Sahel feels its effect (see schematic in Figure 3). The key elements of the teleconnection mechanism are (a) moist convection links surface temperature (more accurately, surface moist energy) to the free troposphere temperature and (b) the tropics can sustain only weak temperature gradients. Where convection happens frequently, the environment comes to be in statistical equilibrium with it: convection dissipates any new Convective Available Potential Energy (CAPE), updrafts from the boundary layer homogenize the atmospheric column, and the final result is that the temperature of the troposphere is close to moist neutrality. With a weak Coriolis effect, the tropics cannot support pressure gradients away from the surface, and thus their free-troposphere temperature must be homogeneous at time scales longer than those of atmospheric waves. Putting these two constraints together requires that the temperature profile of the tropics be that of the moist adiabat corresponding to the precipitation-weighted average of the tropical surface temperature (Flannaghan et al., 2014).

We recognize the effect of this mechanism in the response of the Sahel to ENSO (El Niño Southern Oscillation) variability (Giannini, Biasutti, Held, & Sobel, 2008; Rowell, 2001): During an El Niño, the Warm Pool rainfall extends further into the warmer water, the entire tropical troposphere warms up, and the warm upper-level anomalies increase the atmospheric stability over the Sahel region, thus dampening rain-producing moist convection and causing drought. The same mechanism applies

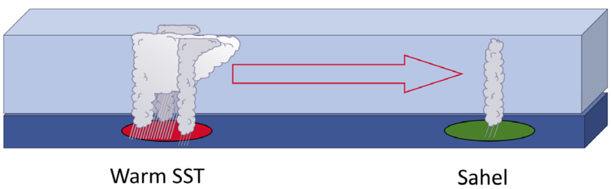


**FIGURE 3** Graphic courtesy of John Chiang. The clouds in the left of the schematic represent the dominant convection center in the tropics, coincident with the warm pool. The Sahel is represented as a lesser area of convection. The two regions are connected via the free troposphere, where temperature anomalies are quickly homogenized by transport

more widely than in the ENSO case—and in particular it ought to apply to the global warming case (Giannini, 2010; Giannini et al., 2008): If the tropical oceans warm, the tropical atmosphere will switch to a warmer moist adiabat. And because warmer moist adiabats are also more stable, the Sahel will experience an upped ante for convection (Chou & Neelin, 2004).

## 2.3 | The West African monsoon

The dynamics of Sahel rainfall variability are inextricably connected with the dynamics of the West African Monsoon (WAM). Associated with ascent in the rain band is a divergent circulation, with low-level southerly flow converging moisture into the Sahel and compensating divergence extending over the depth of the free troposphere. Intertwined with the divergent circulation are the geostrophic circulations: into the Sahara Heat Low (SHL) at low levels and around the anticyclones at mid and upper levels. The anticyclones are associated with two distinct jets, the African Easterly Jet, AEJ, and the Tropical Easterly Jet, TEJ. In Figure 1a we have shown the low-level circulation that accompanies the seasonal rainfall. The map view highlights the westerly component of the monsoonal wind and the easterly component of the Harmattan crossing the Sahara (stream lines); also highlighted is the position of the band of maximum mid-level easterlies that comprise the AEJ. But the zonal component of the flow is not the only important regional feature distinguishing the monsoon circulation from the Hadley cell. Another difference is emphasized in Figure 4 which provides a schematic of the meridional structure of the circulation over West Africa. Superimposed on the deep moist cell that produces the rain band is a shallow circulation: at the surface the southerly flow penetrates well north of the rain band and into the pressure minimum associated with the SHL, shallow and dry ascent maximizes at the ITD, and the northerly return flow of Saharan dry air at about 600mb penetrates into the rain band.

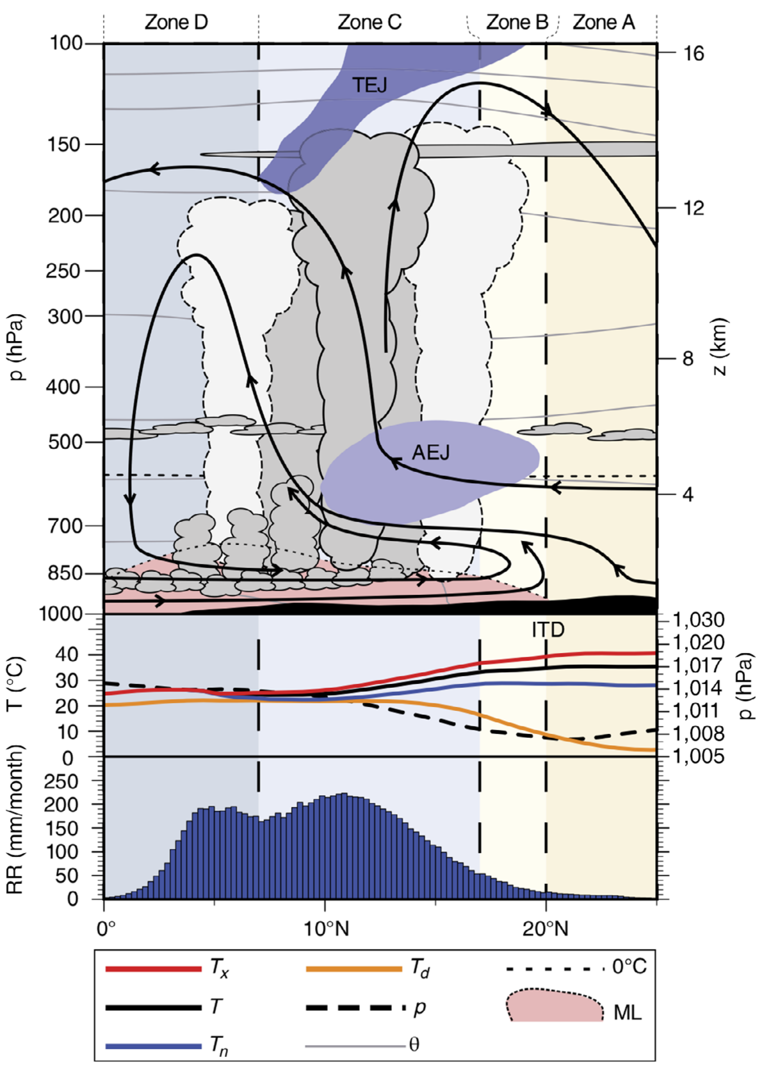


**FIGURE 4** Schematic cross-section of the atmosphere between 10°W and 10°E in July. Shown are the positions of the ITD, upper-level jet streams (African easterly jet [AEJ], tropical easterly jet [TEJ]), the monsoon layer (ML) (as defined by westerly, that is, positive, zonal winds), streamlines, clouds, the freezing level (0°C isotherm), isentropes ($\theta$), minimum (Tn), maximum ($T_x$) and mean ($T$) and dew point temperatures ($T_d$), atmospheric pressures (p), and mean monthly rainfall totals (RR) (Reprinted with permission from Parker and Diop-Kane (2017). Copyright 2017 Wiley)

Many previous reviews (e.g., Nicholson, 2013) have provided an in depth discussion of the dynamics of the WAM. Here we just want to highlight how its complexity leads to several paths of influence on Sahel rainfall. Changes in the position of the SHL, in the strength of the dry advection within the shallow circulation return flow, or in the moisture supplied by the monsoon flow can independently affect the large-scale moisture convergence and atmospheric stability at the latitude of the Sahel. Additionally, because vertical and horizontal wind shears are a source of energy for atmospheric waves, changes in the mean flow can influence rainfall indirectly, via the coupling of synoptic disturbances with moist convection. This coupling is discussed below.

## 2.4 | The weather systems

About 80–90% of the total rainfall amount in the Sahel comes from storms that are especially well organized—they are larger than 80–100,000 km$^2$ and live longer than 6 hr—in spite of those storms being just 11% of the total MCS population (Mathon et al., 2002). Seasonal rainfall variability, thus, likely depends on the controls upon the number and intensity of such organized storms. The complex links between rainfall, mesoscale storms, and synoptic-scale forcings are shown in Figure 5. Wind shear is a key source of organization for convective systems (Houze, 2004) and indeed most squall lines in West Africa are associated with the presence of the AEJ (see also Figure 1a), their tracks shifting north and south over West Africa in association with the jet's seasonal migration (Fink & Reiner, 2003; Mathon et al., 2002). Convective episodes are triggered by thermal

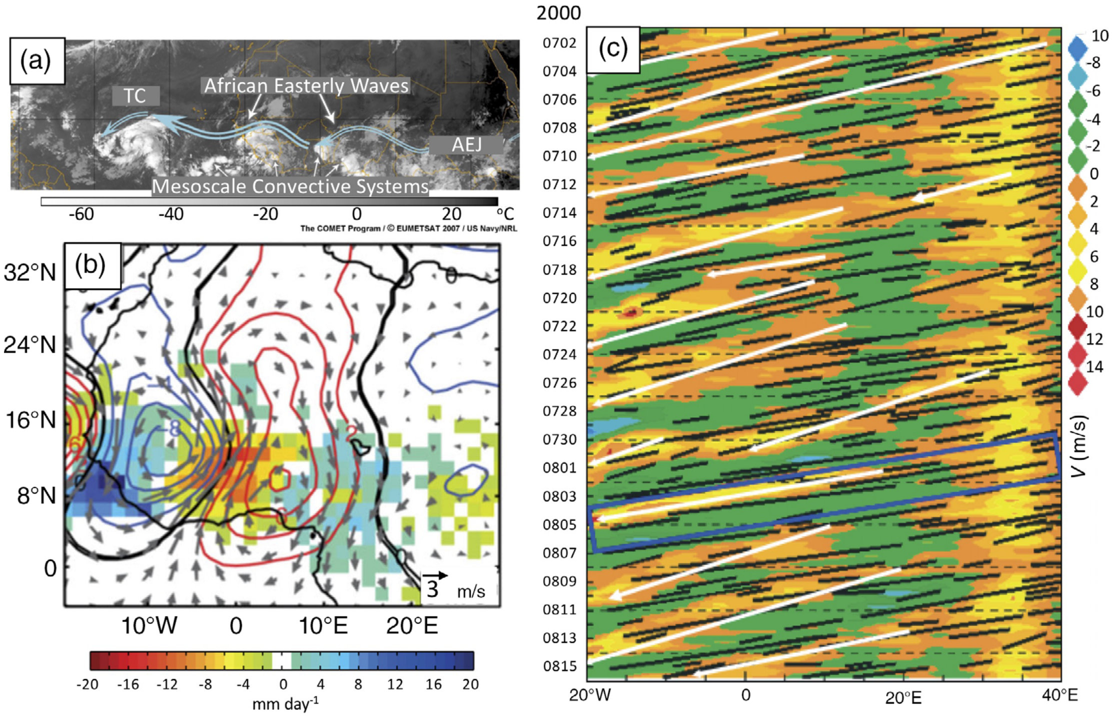


**FIGURE 5** (a) Easterly waves can be observed in satellite imagery because of their associated convection. They appear as circular or banded clouds in satellite images. The source of this material is the COMET (textregistered) website at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR), sponsored in part through cooperative agreement(s) with the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce (DOC). Copyright 1997–2017 University Corporation for Atmospheric Research. (b) Composite anomalies for 3- to 5-day AEWs for the ERA-I and TRMM observations. Vectors are 700 hPa wind anomalies (m/s). Red and blue contours are positive and negative 700 hPa geopotential height anomalies (m) drawn every 2 m. Black contours show the 0 m anomalies. Rainfall anomalies (mm/day) are shaded. Only anomalies above |1| mm/day that are significant at the 95% level according to a two-tailed Student's $t$ test are shown. (Reprinted with permission from Crétat, Vizy, and Cook (2014), Copyright 2014 Springer Nature). (c) Hovmüller (longitude–time) diagram of 850 hPa unfiltered meridional wind (v) and cold cloud streaks axes (black lines) averaged between 5°N and 15°N for the period July 1–August 15, 2001. Colored shading shows v at 2 m/s intervals; northerly winds are gold to red and southerly winds are green to blue. White lines are objectively computed positive meridional wind streaks used to identify AEWs. Cold cloud streaks have $T_b < 233$ K. The blue rectangle identifies the convective systems and AEW from which Tropical Storm Alberto formed (Reprinted with permission from Laing, Carbone, Levizzani, and Tuttle (2008). Copyright 2008 the Royal Meteorological Society)

forcing (especially from elevated terrain, Laing et al., 2008), but they are often organized by the moist and sheared environment provided by AEW, which transport moisture northward between the trough and ridge and enhance the low-level vertical shear ahead of the trough (Figure 5b). The system is coupled, as AEW are also enhanced by moist convection (Cornforth, Hoskins, & Thorncroft, 2009).

While the importance of AEW for weather prediction in West Africa cannot be overstated, at the climate scale (monthly and longer) the connection between rainfall variability and either the number or the amplitude of AEW is still debated. For example, while Lafore et al. (2017) show from case studies how some of the most intense storms in West Africa are associated with the passage of multiple AEWs, in general AEW-forced squall lines "exhibit no extraordinary characteristics (lifetime, propagation speed, size, and rain rate)" (Fink & Reiner, 2003). Moreover, Laing et al. (2008) show that rainfall propagates faster than most AEWs, which would seem to suggest that internal organization of the convective system might be more important than the organization provided by the waves (see Figure 5c). Even so, the variability in the large-scale fields is bound to imprint on the variability of MCSs, as both shear and mid-level moisture can directly affect the organization of convective systems by their influence on evaporative downdraughts, cold pools, and inflow.

## 3 | THE MULTIDECADAL DROUGHT OF THE 20TH CENTURY

In the course of the 20th century, variability in seasonal rainfall totals was large and spatially coherent over much of the Sahel (Figure 6). The first part of the 20th century shows a predominance of anomalously wet years and decades, followed by a decline in seasonal rainfall totals during the later half of the record, with overall low rainfall decades punctuated by devastating short-term droughts such as those of 1972 and 1983–1984 (Figure 6a). The map of the multidecadal rainfall trend (brown colors in Figure 6b) highlights the continental scale of long-term climate change in the Sahel.

The cause of the 20th century droughts has been amply discussed in the literature. In the early 70s—even while meteorologists had started to recognize the possible role of the global atmospheric circulation "teleconnecting" remote regions—the

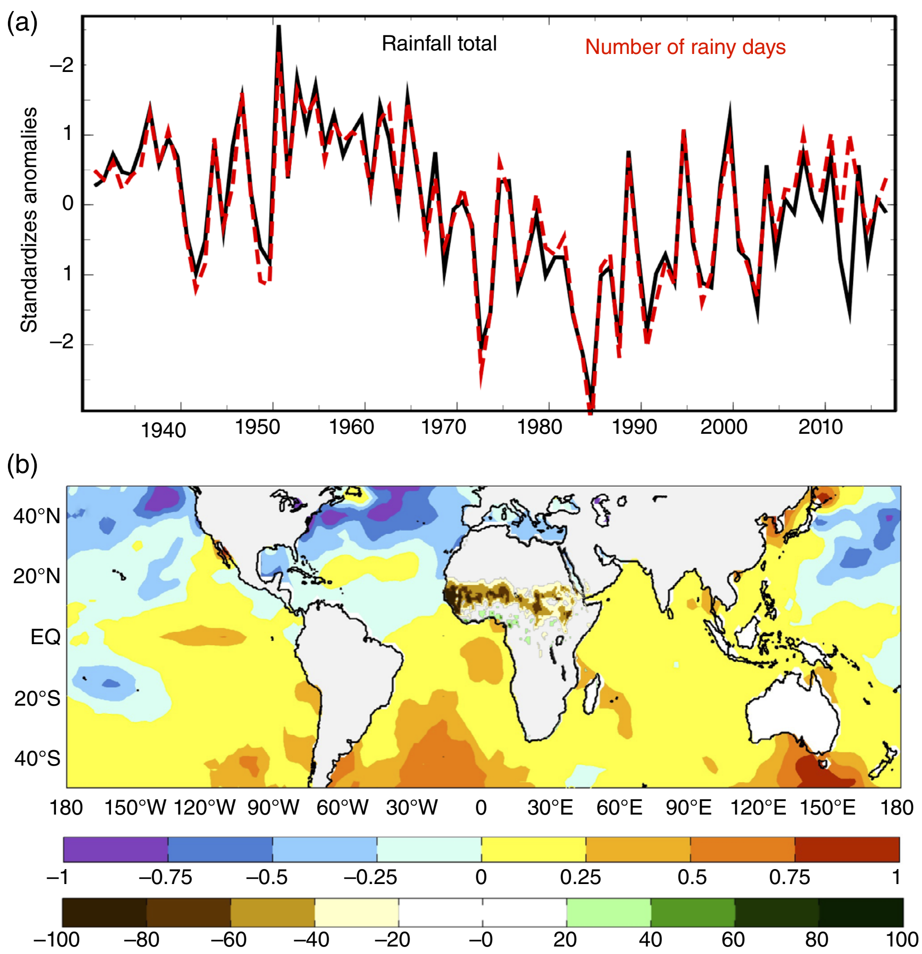


**FIGURE 6** (a) Summer-mean (July to September) standardized anomalies in rainfall totals (black solid line) and number of rainy days (red dashed line) averaged over the region 10°N–20°N and 20°W–30°E (from the University of East Anglia Climate Research Unit gridded data set, TS4.1). (b) Linear trend in summer-mean African rainfall between 1940 and 1985 (brown and green hues) and in annual-mean sea surface temperatures over the same period (blue and orange hues) (Reprinted with permission from Biasutti (2011). Copyright 2011 Nature)

dominant view of the Sahel drought (Charney, 1975) posited that local human activity was driving local climate in a positive feedback loop between poor land use practices, land denudation, and weakening monsoon rainfall. Two scientific developments led to a paradigm shift (Herrmann & Hutchinson, 2005). On one hand, accumulating satellite observation of vegetation distribution were showing that, at the continental scale, vegetation was quick to expand in response to increased rainfall, overcoming the supposed fragility of the natural dryland ecosystem (Herrmann, Anyamba, & Tucker, 2005). Since then, land use by local populations has been linked, more subtly, to both land degradation (Brandt et al., 2017) and land stewardship (Stith et al., 2015), and no unequivocal indication has emerged, either in observations or models, that changes in land use were ever large-scale and homogeneous enough to affect the regional climate (see Box 1). On the other hand, progressively sophisticated computer models of the general circulation of the atmosphere (GCMs) first simulated a decrease in Sahel rainfall when forced with the pattern of the global ocean temperature anomalies of the 70s and 80s (Folland et al., 1986) and, later, were able to reproduce the sequence of pluvial and droughts by including the historical evolution of sea surface temperature (SST), without any forcing from changes in land use (Giannini, Saravanan, & Chang, 2003). It is now accepted that the main source of coherent interannual to interdecadal variability in 20th century Sahel rainfall (the pacing, although not necessarily the full magnitude) has been the variability of SST, while the potential role of natural soil and vegetation processes has been to amplify the remotely driven anomalies (Giannini et al., 2003; Kucharski, Zeng, & Kalnay, 2012; Zeng, Neelin, Lau, & Tucker, 1999).

The pattern of SST anomalies associated with decade-long droughts in the Sahel (Figure 6b) has lent itself to different descriptions. Assuming the point of view linking Sahel rainfall to the planetary ITCZ (Figure 2) leads to an emphasis on interhemispheric gradients, with early work (Folland et al., 1986) emphasizing the SST gradient and recent literature (Hwang et al., 2013; Schneider et al., 2014) emphasizing the gradient in atmospheric energy input. Other studies have attempted to provide a more mechanistic explanation and to connect the SST anomalies in individual basins to specific processes that affect moisture supply and vertical stability. For example, localized warm anomalies in the Indian Ocean generate planetary waves that may lead to more stable profiles in the Atlantic sector and to reduced Sahel rainfall (e.g., Bader & Latif, 2003; Hagos & Cook, 2008). More generally, warmer tropical SSTs induce a more stable atmosphere and thus might induce drought, if not counteracted (see Figure 3). Giannini et al. (2013) have suggested that the nearby Atlantic can provide the needed counteraction. Positive rainfall anomalies in the Sahel ensue when warm temperatures in the subtropical north Atlantic make the low-level monsoon flow sufficiently moist as to overcome the background stability. In their view, then, the tropics as a whole control stability (and control rainfall accumulation through its frequency) and the subtropical north Atlantic controls moisture supply (and controls rainfall accumulation through its intensity).

### BOX 1 DROUGHT, DESERTIFICATION, AND RESILIENCE

On the heels of the “Great Drought” of 1968–1973, the United Nations General Assembly called for international cooperation to combat desertification (which it formally defined in 1994 as “land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities”). The view at the time was that drylands, with their poor climate and soils, were especially fragile and vulnerable to human land use. This, coupled with the assumption that desertification might itself force drought (Charney, 1975), had led to a forecast of spiraling degradation. This view has since been challenged by both the natural and the social sciences (Herrmann & Hutchinson, 2005). Ecological studies have emphasized how drylands are highly variable ecosystems, for which a dynamic nonequilibrium is to be expected. Their health is better monitored by slow-varying variables such as soil fertility, rather than by variables such as vegetation cover or crop yields that respond fast to the vagaries of precipitation, pest outbreaks, and the like (Reynolds et al., 2007). Indeed, as rainfall totals have increased since the mid-1980s, vegetation has expanded in what has been known as a re-greening (Dardel et al., 2014). Similarly, socioeconomic studies have highlighted how rural populations employ risk-spreading (e.g., economic diversification) and coping strategies (e.g., labor-intensive conservation practices) to reduce stress on both their livelihoods and the environment (Mortimore, 2010; Reynolds et al., 2007). Still, soil erosion, loss of soil fertility, and loss of biodiversity remain widespread problems. As the climate changes outside the realm of modern experience, an alliance of local and science-based knowledge is needed to build resilient human and environmental systems in the Sahel (Maestre et al., 2016).

Whether the subtropical north Atlantic is the key region for moisture supply remains unproven. Lagrangian calculations of moisture sources for West Africa are at odds with this interpretation, as they indicate that Sahel rainfall originates from the South Atlantic and the African continent itself (Keys, Barnes, van der Ent, & Gordon, 2014).[2] It seems more likely, therefore, that warm anomalies in the subtropical north Atlantic affect Sahel rainfall through their effect on the temperature, humidity, and circulation over the Sahara, in the same fashion as has been suggested for warm anomalies in the extra-tropical north Atlantic (Liu & Chiang, 2012; Park, Bader, & Matei, 2015) or the Mediterranean (Park, Bader, & Matei, 2016).

The mechanisms by which a northerly flow of anomalous warm and moist air coming across the Sahara can affect Sahel rainfall are multiple. In general, altering the moisture profile above the boundary layer modulates convective inhibition (the effect of a stable or dry layer of air that caps vertical motion close to the ground) as well as the effect of entrainment on convective plumes (as dry air mixing in during ascent dilutes the energy available for convection). These processes would seem to be quite fundamental, in view of the strong association between total column water vapor and daily rainfall that is a hallmark of tropical rainfall (Bretherton, Peters, & Back, 2004). Nevertheless, in the Sahel variations in the temperature profile dominate over humidity in modulating the seasonal-scale variations of the level of free convection and of the occurrence and intensity of deep convection (Kollias, Miller, Johnson, Jensen, & Troyan, 2009). It remains to be seen if temperature remains the dominant factor for decadal-scale Sahel drought.

Furthermore, temperature and humidity trends within the Sahara might have affected Sahel rainfall indirectly, by changing the large-scale circulation. One hypothesis is that the advected warm (cold) temperature anomalies or the radiative effect of the positive (negative) moisture anomaly would cause the SHL to shift to the north (south). This would result in a shift of the mid-level divergence and would allow more/less rainfall at the latitude of the Sahel (Evan, Flamant, Lavaysse, Kocha, & Saci, 2015; Shekhar & Boos, 2017; Zhai & Boos, 2017). Observations of long-term trends in the Sahara (whether they be of moisture, temperature, or surface pressure) are unfortunately not available, preventing the testing of these mechanisms for the 20th century drought. Yet, one indirect piece of evidence might be found in simulations of the direct effect of greenhouse gases, that is, the effect that results in atmosphere-only GCMs from increasing atmospheric long-wave absorption while keeping SST unaltered. In these simulations (Gaetani et al., 2016), the Sahara warms, the heat low shifts north, and rainfall in the Sahel is enhanced throughout the rainy season. We can surmise that the Sahel response would be the same if the Sahara warming were due to advection of SST-forced anomalies, instead of being forced locally by radiative fluxes.

No matter the details of the mechanisms, theory, modeling, and observations, all indicate that the Sahel drought was driven by processes that were global in scale. Yet, processes that are local to the Sahel—biogeochemical and biophysical vegetation and soil processes that affect the surface fluxes of matter and energy—are known to be important as amplifiers of the anomalies (Kucharski et al., 2012; Zeng, Neelin, & Chou, 2000). At the timescales of paleoclimatic changes, feedbacks involving land cover types and dust sources are believed to be key to the establishment of climatic anomalies (Kutzbach, Bonan, Foley, & Harrison, 1996; Mohtadi, Prange, & Steinke, 2016; Pausata, Messori, & Zhang, 2016; Timm, Köhler, Timmermann, & Menviel, 2010). At the shorter time scales of interest here, it is sufficient to consider moisture and energy feedbacks involving plant function and soil properties.[3]

According to recent work (Taylor et al., 2011; Taylor, de Jeu, Guichard, Harris, & Dorigo, 2012), a negative feedback between soil moisture, surface convergence, and rainfall depresses rainfall initiation over wet patches. Yet, this mechanism influences mesoscale variability without carrying over to regional rainfall (Guillod, Orlowsky, Miralles, Teuling, & Seneviratne, 2015; Seneviratne et al., 2010). At the regional scale of the Sahel, the traditional view of a positive feedback due to moisture recycling still holds: a wet surface can provide more water vapor to fuel more convection and rainfall (Brubaker, Entekhabi, & Eagleson, 1993). Nevertheless, it is unclear if a positive land-surface feedback is a persistent characteristic of Sahel rainfall. Berg, Lintner, Findell, and Giannini (2017) have shown that the positive feedback of moisture recycling interacts with the effect that moisture gradients have on surface temperature and the regional circulation (the shallow meridional circulation that penetrates north into the Sahara, and the strength and position of the AEJ), leading to divergent feedbacks in these models. Berg, Lintner, et al. (2017) were analyzing global warming simulations, but shortcomings in the representation of the full land-surface feedbacks might also explain the inability of most GCMs to reproduce the amplitude of observed 20th century trends (Biasutti, 2013).

The multidecadal swings in seasonal rainfall totals just discussed can be explained in terms of variability in the number of wet days (see Figure 6a). In the most recent period, though, the relationship between rainfall frequency and rainfall accumulation weakened somewhat, suggesting that variations in rainfall intensity are nonnegligible even at the regional and seasonal scale. These trends are discussed in the next section.

## 4 | RECENT CHANGES IN RAINFALL CHARACTERISTICS

Observations show 1984 to be the driest year on record in the Sahel. Seasonal rainfall totals trended upwards since then (Dai et al., 2004), mesoscale disturbances have been more extensive and intense (Bell & Lamb, 2006), and vegetation cover has increased over the same period (Dardel et al., 2014). Thus, the literature refers to the latest decades as a period of recovery for the Sahel (Nicholson, 2005). Farmers on the ground, on the other hand, have questioned whether this is a return to past conditions; instead, they have emphasized changes in the characteristics of the rainy season (its intermittency, variability, and prevalence of intense events) and enduring challenges for agriculture (Tambo & Abdoulaye, 2012; West, Roncoli, & Ouattara, 2008). A growing literature based on daily gauge data and high-resolution satellite estimates is beginning to corroborate anecdotal accounts and on-the-ground experiences of increasing extreme and erratic rainfall.

The assessment of trends in the characteristics of rainfall is complicated by the quality of the observations and by the intrinsic noisiness of the record (especially for extreme events). Using satellite-based rainfall data sets over the western Sahel for the period 1998–2013, Odoulami and Akinsanola (2017) show no regionally coherent significant trends in the intensity of extreme rainfall and a weak (and spatially incoherent) trend toward less-frequent intense rainfall, even as total rainfall and rainfall frequency trend toward wetter conditions. Yet, Salack, Saley, Lawson, Zabré, and Daku (2018) show that, taken together, 72 gauge records for the western Sahel do show an increase in the 99th percentile daily rainfall threshold and that in the most recent decade extreme rainfall is more extreme than it was in the early 1960s. Gridded indices of 95th percentile rainfall suggest the same conclusions (Sanogo et al., 2015). Giannini et al. (2013) and Lodoun et al. (2013) analyzed the trends in rainfall from gauges in Burkina Faso and Senegal and found that in the decades of rainfall "recovery" the mean intensity of daily rainfall exhibited the steadiest trend and a dominant role in the recovery, above changes in rain frequency. Sarr, Zoromé, Seidou, Bryant, and Gachon (2013) objectively identified from station data in Senegal the switch from drying to wetting in the mid 1980s and showed that in the second part of the record the trend in rain frequency is not as strongly positive as the trend in rainfall intensity; at the same time they did not detect any signal in indices of extreme rainfall.

A balanced assessment of the recent changes in the character of the rainy season in West Africa is given by the careful study of Panthou, Vischel, and Lebel (2014), who looked at 43 stations in Benin, Burkina Faso, and Niger. When epochal means in intense rainfall (above the 40-mm threshold) occurrences were compared directly, the station network showed no coherent change, with half the stations indicating an increase in frequency of occurrence and half indicating a decrease. But when the noisiness of the data was reduced by using appropriate statistics for extreme distributions and by considering trends in total rainfall accumulation, they were able to show that the proportion of annual rainfall associated with extreme rainfall has increased from 17% in 1970–1990 to 19% in 1991–2000, to 21% in 2001–2010. In their words: "This tends to support the idea that a more extreme climate has been observed over 2001-2010: this climate is drier in the sense of a persisting deficit of rainfall occurrence compared to 1950-1969, while at the same time there is an increased probability of extreme daily rainfall." The same sentiment is expressed by Salack, Giannini, Diakhaté, Gaye, and Muller (2013), who compared the timing and frequency of dry spells within the rainy season of West Africa and concluded that recent years have experienced seasonal rainfall amount close to normal, but were more susceptible to extreme dry spells that would cause false starts and early cessation of the cropping season.

A different approach was taken by Taylor et al. (2017). Their study does not look at rainfall directly, but uses Infra-Red satellite images to identify storms. This has the advantage of providing a complete and homogeneous dataset that covers all of Africa for the period 1982–2016 and allows them to identify robust trends. They find that, over the Sahel, the most extreme storms tripled over that time and that their contribution to the seasonal rainfall has grown from 15% to above 20%, consistent with the gauge-based estimates reported above.

The relationship between storms and environmental variables suggests that the observed intensification of storms follows from the intensification of the shallow circulation and the AEJ. Increase flow of mid-level warm air and dry air act to suppress moderate convection, but once MCSs get triggered the same flow acts to intensify them via enhanced CAPE and evaporative downdraughts. A stronger jet also leads to more intense MCSs, as it provides the shear to organize convection and, possibly, to increase triggering and intensification of convection by AEWs. These mechanisms are all directly linked to a warming Sahara, and as such have been portrayed as a possible sign of anthropogenic influence on the characteristics of storms, but formal attribution has not been achieved yet.

## 5 | DETECTING ANTHROPOGENIC TRENDS

The effects of the emissions of greenhouse gases and aerosol particles, the byproducts of industrialization, have already been unequivocally detected in the warming of the Earth since the 19th century. Given the established evidence that Sahel rainfall responds to anomalies in regional energy fluxes and in global SST, we can ask what part of the observed variability was ultimately driven by past anthropogenic emissions and what will be the impact of future emissions.

The tools to answer such questions are computer models that are driven by the history of atmospheric composition (Coupled ocean and atmospheric Global Climate Model) or the history of anthropogenic emissions (Earth System Models, which simulate the chemical and biological systems that process anthropogenic emissions and calculate the resulting changes in atmospheric composition).[4] Dozens of such models exist (Taylor, Stouffer, & Meehl, 2012), with different levels of complexity and performance, and the global climate simulated by each differs in some measure from both the observed climate and that of other simulations. Such disparities derive from systematic model errors (biases) and from the chaotic nature of the climate (internal variability). The mean of the ensemble of simulations provides our best estimate of the forced climate variations (signal) and the intra-ensemble spread is one (likely optimistic) indicator of the uncertainty of such estimate (noise).

Many studies have established the presence of a forced component in the Sahel drought; it is the magnitude of such component that is still vigorously debated. Qualitatively, we understand the drying of the Sahel from the 1960s through the 1980s as influenced by the emissions of reflective aerosols (mostly sulfates) in North America and Europe. These aerosols cause cooling via scattering of solar radiation away from the surface both directly and because they make clouds brighter and more long-lived. But aerosols are easily removed by the atmosphere (either by dry deposition or by rainfall), so that their cooling effect is regional and hemispheric, not global (Myhre, Shindell, Bréon, & Table, 2013). The cooling of the NH relative to the SH is expected to shift the zonal mean ITCZ to the south (Schneider et al., 2014, Figure 2b), and the drying of the Sahel during these decades has indeed been interpreted as part of the ITCZ response to the aerosol forcing (Ackerley et al., 2011; Biasutti & Giannini, 2006; Booth, Dunstone, Halloran, Andrews, & Bellouin, 2012; Hwang et al., 2013; Rotstayn & Lohmann, 2002). At the same time, natural variability in the ocean–atmosphere system can also create a hemispheric gradient of SST and especially strong anomalies in the Atlantic basin,[5] either through a change in the deep oceanic circulation (Zhang & Delworth, 2005) or through atmospheric fluxes acting on the oceanic mixed layer (Clement et al., 2015). The relative importance of these mechanisms—a radiatively forced cooling, a rearrangement of the oceanic circulation, and atmospheric noise reddened by oceanic processes—in creating the observed SST anomalies is model dependent, with uncertainties deriving mostly from the treatment of the aerosol–cloud interactions (Zhang et al., 2013) and the strength of the simulated natural variability in the oceanic meridional circulation (Ba et al., 2014). The task of going beyond the attribution to external forcing of SST anomalies to attribute Sahel rainfall anomalies themselves to such forcings is especially challenging. Because few models are capable of reproducing the full range of observed variability in the latter (Biasutti, 2013), it is difficult to estimate what fraction of the observed trend ought to be reproducible (and attributable to external forcing), and what fraction is purely atmospheric noise.

The debate on the detection of anthropogenic signals extends to the mechanisms of recovery of the rainfall since the 1990s. If oceanic internal variability is dominant, drying, and recovery would naturally oscillate and their pacing would be well captured by an index of SST variability in the north Atlantic. If aerosols are dominant, the recovery of the rains would follow from reduced sulfate emissions in the United States and Europe and thus a reduction in the inter-hemispheric aerosol loading (even though pollution of this kind has increased in Asia over the same period so that global sulfate aerosol forcing has held steady; Myhre et al., 2013). A third option is also possible: Greenhouse gas (GHG) emissions have increased unabated over the most recent three decades—can they be causing positive rainfall anomalies in the Sahel?

According to the ensemble mean of the latest generation of climate models, when the GHG-forced signal is dominant (e.g., in idealized simulations or scenarios for the 21st century). Sahel rainfall does indeed increase (Biasutti, 2013 and Figure 7). Yet, model disagreement is still substantial, which complicates the detection of an emerging GHG signal in the Sahel recovery. We make sense of the model disagreements as a consequence of the two (direct and indirect) paths in which GHG affect Sahel rainfall: via increased energy input into the land surface and the atmosphere and via changes in the global SST.[6] The direct effect of GHGs is to wet the Sahel for all models (Biasutti, 2013; Gaetani et al., 2016). This is consistent with the interpretation of the monsoon as a facet of the energetically direct tropical circulation (Biasutti et al., 2018) and, mechanistically, with the warming over the Sahara and the strengthening of the monsoonal circulation (Biasutti, Sobel, & Camargo, 2009; Haarsma, Selten, Weber, & Kliphuis, 2005). The key aspect of the anomalous circulation is not the deepening of the heat low and an intensification of the inflow at low level, but the low's shift northward and the weakening of the dry intrusion by the return flow of the shallow meridional circulation (Gaetani et al., 2016; Shekhar & Boos, 2017). In contrast, SST-mediated Sahel rainfall anomalies are less robust across models. This is for two reasons: First, because of the uncertainty in the pattern of projected anomalies, specifically in the degree of warming in the North Atlantic (Giannini et al., 2013; Park et al., 2015) and the Mediterranean (Park et al., 2016) relative to the overall warming. Second, because of the different atmospheric sensitivity to the same oceanic anomalies (Biasutti, Held, Sobel, & Giannini, 2008; Gaetani et al., 2016; Held,

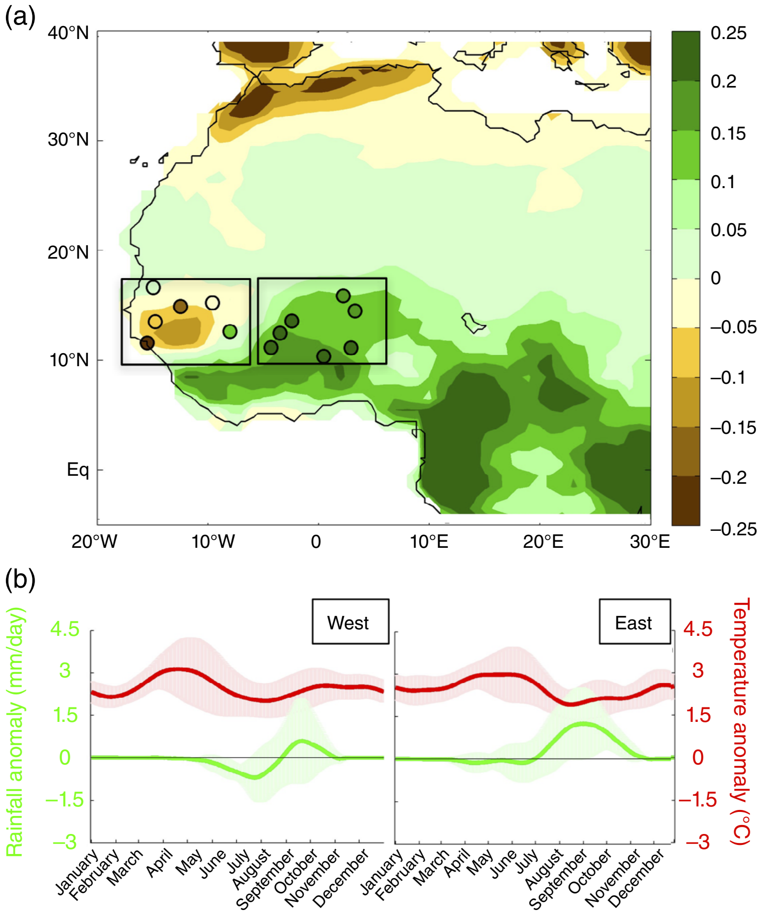


**FIGURE 7** Top multimodel averaged, annual mean rainfall anomalies (in mm/day) between future and past (2031–2060 in the RCP8.5 scenario and 1960–1990 in the Historical scenario), averaged over eight climate models. Field values are the anomalies in the raw model output (regridded to 1° resolution). Filled circles are anomalies in the bias-corrected output. The boxes indicate the sites of West Sahel and Central Sahel. Bottom: Smoothed daily anomalies in rainfall (mm/day, green) and temperature (°C, red) averaged over the sites of (left) West and (right) Central Sahel. The solid line is the multi-model mean, the shading represents 1 *SD* scatter (Reprinted with permission from Guan, Sultan, Biasutti, Baron, and Lobell (2017). Copyright 2017 Elsevier)

Delworth, Lu, Findell, & Knutson, 2005; Hill, Ming, Held, & Zhao, 2017; Park et al., 2015). Different atmospheric sensitivities to overall warming are likely to stem from how the models produce convective rainfall given a certain large-scale atmospheric environment.[7] Different responses to the same SST patterns are not easily explained (Rowell, Senior, Vellinga, & Graham, 2015). Nevertheless, there is qualitative agreement across models that the indirect effect of GHG is to dry the Sahel (Biasutti, 2013). Thus, the overall effect of GHG is the sum of competing direct and indirect effects.

The signature of GHG forcing might be easier to detect in the appearance of zonal asymmetries in Sahel rainfall (Figure 7a). GHGs wet most of the Sahel, but not its westernmost portion. This zonal asymmetry likely derives from the deepening of the SHL. Because the low is not zonally symmetric but is concentrated over the western Sahara, an enhanced heat-low circulation contributes opposite-sign anomalies in the east–west direction, as the geostrophic wind advects dry subtropical air to the western Sahel and moist tropical air to its eastern part (Lavaysse, Flamant, & Janicot, 2010). Warming of the Sahara either directly by GHG or through the effect of warm and moist advection from a warmer ocean have the same effect on the position and strength of the SHL, thus the asymmetry between the eastern and western Sahel rainfall anomalies is the result of the combined (direct+indirect) response to GHG (Gaetani et al., 2016) and can supply a robust metric for the detection of GHG-induced trends.

Another robust aspect of the Sahel response to GHG is its seasonality, in that the wetting is mostly confined to the late portion of the rainy season (Biasutti & Sobel, 2009, Figure 7b). We expect this seasonal asymmetry to be specific to the GHG forcing. Thus its emergence could help us detect a GHG signal in the Sahel. The reason why we expect this seasonal asymmetry is the following (see also how it was formalized by Song et al., 2018): The early rainy season is a time when the conditions for convective instability are rarely met—so an increase in global atmospheric stability will exacerbate inhibition and lead to drying (Chou & Neelin, 2004; Giannini, 2010; Lintner & Neelin, 2007). In this view, the role of direct GHGs forcing is to provide the energy necessary to overcome the inhibition and switch from a dry to a wet regime (Giannini, 2010; Seth et al., 2013). Conversely, the core rainy season is a time when ascent is always possible—so an increase in global specific humidity will intensify rainfall (Held & Soden, 2006; Huang, Xie, Hu, Huang, & Huang, 2013).

The fingerprint of GHG on Sahel rainfall outlined above is muddled by substantial uncertainties. First and foremost, there remain outlier models that project Sahel rainfall anomalies with different seasonal patterns and opposite annual-mean signs; these are state-of-the-art models without any egregious deficiencies and cannot easily be dismissed (Rowell et al., 2015). Second, even among the models that agree on the sign of the GHG-induced signal, there are large differences in the magnitude of the rainfall changes and in the spatial and seasonal patterns: the boundaries between negative and positive anomalies in the east–west direction and between early and late season are highly variable across models (Biasutti, 2013). These uncertainties hamper the unequivocal definition of a global warming signal and the detection of its emergence.

Nevertheless, we note that some features of the expected pattern of GHG-forced anomalies have been recorded in observations. For example, Ali and Lebel (2009) and Lebel and Ali (2009) noted that, by 2007, western regions of the Sahel (Senegal and western Mali) had not recovered from drought, while regions further to the east (Burkina Faso and Niger) had done so, in qualitative agreement with expectation from GHG-forced simulations. In contrast, Zhang, Brandt, Guichard, Tian, and Fensholt (2017) reported a stronger recovery of rainfall totals for the 1983–2015 period in the broadly defined West African Sahel, compared to regions to the East (Chad, Sudan), but lack of ground calibration for the satellite-based data set in the latter region suggests caution. Panthou et al. (2018) (reproduced in Figure 8) show that the Western and Eastern portions of the Sahel do not vary in unison and that the intensity of precipitation has increased the most in the East. Looking at the seasonality of rainfall, Usman, Nichol, Ibrahim, and Buba (2018) showed that rainfall increases in Niger were mostly concentrated in the later part of the growing season and Lodoun et al. (2013) reported a delaying trend in the cessation of the rainy season of Burkina. Sanogo et al. (2015) also reported that positive rainfall trends in the West African Sahel are strongest in August and September and extend into October, outside the traditionally-defined rainy season. Overall, while a confident attribution is still premature, the spatial and seasonal patterns of recent rainfall anomalies seem to suggest that GHG forcing has been contributing to the observed recovery.

Moreover, one robust consequence of global warming is the increase of mean and extreme rainfall intensity (O'Gorman & Schneider, 2009; Sillmann, Kharin, Zwiers, Zhang, & Bronaugh, 2013) and the increase of Sahel rainfall since the 1980s is due in nonnegligible part to an intensification of rainfall events, as discussed above. Recent temperature trends over the Sahara are as well consistent with GHG forcing, both in the spatial pattern and in the seasonality (Vizy & Cook, 2017b) and, as pointed out by Taylor et al. (2017), this would also imply a robust effect of GHG on the occurrence of intense rainfall. This correspondence is tantalizing, yet it is not easily explained. In observations, storms (at least the most intense ones) have intensified by becoming more organized due to the increased shear, but in current-generation climate models the spatial resolution is too coarse to represent mesoscale organization and convective parameterizations are insensitive to shear. In order to determine whether the observed intensification of Sahel rainfall is consistent with the emergence of a GHG-forced signal, we need to elucidate the relative roles of thermodynamic moisture increase and dynamic organization around shear in driving it.

Finally, we address the possibility that anthropogenic land use and land cover changes have had a role in either the drought or the recovery of Sahel rainfall. The latest assessments by regional and global models (Boone et al., 2016; Hagos et al., 2014) indicate that forcing the atmosphere with a steady and drastic reduction in vegetation cover (such as changing broadleaf trees to broadleaf shrubs and grasses and shrubs to bare soil over all of West Africa) induces a rainfall reduction ranging from

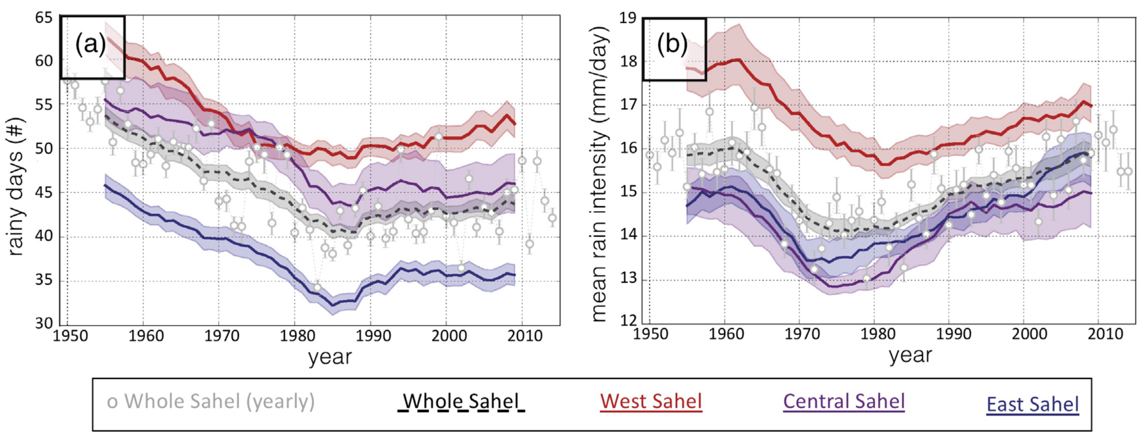


**FIGURE 8** Evolution of (a) the mean number of rainy days and (b) the mean intensity of rainy days (mm/day) over the whole Sahel and subdomains (West, Central, and East Sahel). Error bars (resp. shaded area) delineate 80% confidence intervals for annual values (resp. 11 year rolling mean) (Reprinted with permission from Panthou et al. (2018). Copyright 2018 the Creative Commons Attribution 3.0 license)

4 to 25%, which is much less than observed. In reality, most of the vegetation changes between 1950 and 1990 were a response to changes in rainfall, rather than vice-versa (see sidebar), and trends since the 90s have not been spatially homogeneous: woody cover has largely increased in drylands, as a result of increased rainfall (Dardel et al., 2014) and, to some extent, of conservation practices (Stith et al., 2015), and has decreased only in humid zones with high population growth (Brandt et al., 2017). Thus, while vegetation processes may have acted to amplify externally driven climate anomalies at the decadal scale, anthropogenic changes in land use and land cover were at most a minor source of trends.

## 6 | INTERPRETING PROJECTIONS OF SEASONAL RAINFALL

The models that we use to peer into the climate of the future are close cousins of weather prediction models, but they are tasked to forecast a climate that has no past analog and the long time scale of the projections prevents the climate models from being validated in the same way as weather models are. Therefore, the climate anomalies simulated for the coming decades are not a prediction to take at face value. Nevertheless, they are our best informed guess of what the future will hold. This session discusses, in the context of Sahel rainfall, two issues that are key for a wise use of climate projections: How should we handle model consensus when all models have common systematic biases? How should we handle model disagreement in climate projections?

### 6.1 | How to interpret consensus when all models have common systematic biases?

It is often assumed that model agreement means less uncertainty in the prediction. This is a warranted conclusion in those cases in which the simulated response is consistent with established theory—the obvious example being the projection of warming for the global mean temperature. Yet there are cases in which theory does not set firm expectations and common systematic biases across models suggest caution, as all models might be wrong in the same way.

Two common model shortcomings have the potential to greatly affect projections of Sahel rainfall. First, the equatorial ocean–atmosphere system is poorly simulated, leading to biases in the simulated structure of the ITCZ and of El Niño anomalies (Li & Xie, 2014). It has been suggested (Coats & Karnauskas, 2017) that a systematic bias is why CMIP-class models simulate equatorial warming in historical simulations, contrary to observations. The equatorial warming is also a major feature of future projections. What would it mean for the Sahel if those projections were to be proven wrong? Following our current understanding of the mechanisms by which the tropical SSTs affect Sahel rainfall, we speculate that the wetting signal would strengthen without the additional warming in the equatorial Pacific, because of a lesser increase in stability and a more pronounced relative warming in the Atlantic and Mediterranean.

A second shortcoming of GCMs is their misrepresentation of development and organization of rain systems over land. One known consequence is that the modeled profile of time-mean ascent is biased toward deep clouds (Roehrig, Bouniol, Guichard, Hourdin, & Redelsperger, 2013). We can speculate that if the models simulated a more realistic bottom-heaviness in the ascent profile, the simulated Sahel rainfall would probably be less susceptible to the increase stability driven by the tropical warming (Giannini et al., 2013; Hill et al., 2017), resulting in even wetter conditions in response to GHG. Limitations in the convective parametrization have also been implicated in common biases in the diurnal cycle, the intensity distribution, and the temporal coherence of rainfall (Covey et al., 2016; Roehrig et al., 2013). The effects of these systematic biases on the response to GHG are not amenable to speculation, as they depend on the interaction of clouds and radiation.

Convection resolving simulations are coming online and may provide further guidance (Marsham et al., 2013; Stratton et al., 2018; Vizy & Cook, 2017a). These simulations are an important addition to our toolkit. In particular, because they resolve the dynamics of rain-bearing systems, they provide our best assessment of the mechanisms by which rainfall characteristics and intensity distribution might change in the coming decades. Nevertheless, they are not a panacea that can increase overall model reliability and reduce uncertainty in projections. For one thing, even though they have improved rainfall characteristics at the weather scale, models that resolve the convective scale can show persistent regional and seasonal biases (e.g., in Stratton et al. (2018) summertime rainfall biases are much reduced near orography, but not elsewhere). Additionally, most convection-resolving simulations are performed on regional domains and thus depend on boundary conditions from global models, which are likely to affect the character of the regional projections (Kendon et al., 2017). The experience with regional climate models paired with different global models suggests that convection-resolving models would both inherit uncertainties from the driving models and introduce their own (Mariotti, Coppola, Sylla, Giorgi, & Piani, 2011; Pinto, Jack, & Hewitson, 2018). Moreover, the coupling between the atmosphere and the vegetation might be as significant as the characteristics of rainfall in determining outcomes such as land productivity (see Box 2), so that one should be mindful of the trade-offs between prioritizing model resolution (cloud-resolving models) or model complexity (earth system models).

## 6.2 | How to handle model disagreement in climate projections?

At the other end of the uncertainty spectrum is the possibility that the ensemble of coupled models provides a broad range of contradicting projections (Chadwick et al., 2016) or that outlier models buck what would otherwise be a consensus (Held et al., 2005). Is it still possible to extract reliable information?

Climate models are routinely validated against observations, but there is no single metric by which we can rank models from worst to best (Gleckler, Taylor, & Doutriaux, 2008; Pierce, Barnett, Santer, & Gleckler, 2009). Depending on our research interest, we may focus on the distribution of clouds, or the position of the wind jets, or the timing of monsoon onset, and different models would rank differently for these different metrics.[8] The impact literature has often focused on assessing the consequence of climate change by considering anomalies that are either the middle-of-the-road estimate or the estimate by some "better" model. This approach is risky, because it does not consider the full spectrum of possible futures (Kendon, Jones, Kjellström, & Murphy, 2010). Better to embrace the diversity of model projections as a (partial) estimate of the uncertainty in the climate forecast. Unfortunately, this requires large resources, especially when dynamical downscaling is required, and might not always be advisable.

An emerging approach was described by Zappa and Shepherd (2017). Their starting point is that, in most cases, uncertainty in climate sensitivity translates into stronger or weaker regional anomalies for warmer or cooler futures, but it does not cause uncertainty in the sign of regional changes, while the intractable uncertainty in regional climate change comes from discrepancies in projected circulation anomalies (Collins et al., 2018; Xie et al., 2015). Observed teleconnections and theoretical arguments are then used to provide a link between qualitatively different global patterns (the "storylines") and regional circulation anomalies. A full range of plausible future climate anomalies is thus created from plausible storylines, and an optimal set of boundary conditions for impact studies is obtained by selecting for downscaling at least one global model per storyline. This approach has not yet been exploited for African climate, but it promises to be useful to integrate low-probability-high-risk scenarios in impact studies. Given what we have learned about the mechanisms driving Sahel rainfall anomalies, we suggest that

### BOX 2 HEAT, ARIDITY, AND YIELDS IN A HIGH $CO_2$ WORLD

Crop models driven by idealized or projected changes in atmospheric drivers (temperature, rainfall, radiation) simulate a decline in grain yields across the entire Sahel due primarily to increased mean temperature, with potential wetter or drier conditions and elevated $CO_2$ concentrations acting to modulate the loss (Sultan & Gaetani, 2016). But the effect of warming on vegetation has itself generally been interpreted as increased water stress, via an increase in water vapor deficit (which is a robust consequence of warming through the Clausius Clapeyron equation). Commonly used measures of aridity include an evaporative demand term and thus increase with increases in vapor deficit (Scheff & Frierson, 2015)—even in regions where precipitation is not declining.

Within such a perspective, evapotranspiration variability is seen as driven by the atmospheric demand; in reality, plants exert a much stronger control. High $CO_2$ concentration affects the physiological behavior of plants: $CO_2$ fertilization increases vegetation and leaf area but at the same time reduces stomata opening. The net effect is to limit transpiration, which in turns leads to additional warming and drying of the near-surface atmosphere. But if a reduction in evapotranspiration is, *in part*, a cause of warming, the latter should not be used to infer changes in the former. Yet, this is what is done in offline calculations of aridity, which therefore overestimate the effect of warming, water stress, and crop loss (Berg & Sheffield, 2018). Coupled calculations sidestep this problem and generally indicate overall increase of net primary productivity even where aridity measures trend up. In the Sahel, coupled models indicate negligible change in net primary productivity and root-zone soil moisture (Berg, Sheffield, & Milly, 2017; Wieder, Cleveland, Smith, & Todd-Brown, 2015).

Even so, bulk measures of greenness do not capture grain yield (total mass in seed filling, as opposed to leaf area), nor the nutritional value of the grains (which is likely to decrease as the growing season shortens; Uddling, Broberg, Feng, & Pleijel, 2018). A refined assessment using climate-crops coupled models and real-world manipulations is necessary to fully understand the effect of $CO_2$ on agricultural productivity.

the relevant storylines would describe (a) a range of developments for the SHL and (b) a range of SST gradients between the global tropics and the northern Atlantic. For the former, model uncertainty lies mostly in the specific location of the anomalous low and is most relevant for the determination of subregional gradients in rainfall anomalies. For the latter, the uncertainty is much larger, as it includes uncertain outcomes in the ocean dynamic response in the Pacific (resulting in El Niño-like or La Niña like SST anomalies) and in the Atlantic overturning circulation.

A complementary approach would seek to reduce uncertainty regarding the steps to be taken for adaptation, rather than in the climate information that underpins it (Kalra et al., 2014). For example, adaptation planning might start with the assessment of a system's vulnerabilities to climate and test whether an adaptation is robust to uncertain climate scenarios or whether the uncertainty is so great that an adaptive management plan is needed. This approach requires that decision-makers and scientists collaborate in the co-production of climate information (Kniveton et al., 2015), namely to determine and explore the range of plausible scenarios relevant to a given adaptation problem.

## 7 | CONCLUSIONS

Decades of research have made clear that seasonal rainfall variability in the Sahel can be explained as the response to anomalies in the atmospheric circulation that are planetary or regional in scale and that are mostly driven from afar—by changes in the surface temperature of the global oceans, by direct effect of increasing anthropogenic emissions of pollutants, or by a combination of both. The fact that the dominant drivers of Sahel rainfall seasonal accumulation are large scale (and thus well resolved by the current generation of climate models) lends some confidence in projections for the future. These suggest increases in rainfall totals in the central and eastern Sahel, but decreases in the westernmost regions and a concentrated rainy season characterized by more intense and intermittent rainfall, drier condition at the onset, and wetter conditions during the core and the demise of the growing season. Yet, uncertainty in future projections remains, due to both disagreement across models and the unresolved presence of systematic biases common to all state-of-the-art climate models.

An additional challenge is posed by the need for climate information at spatial scales much smaller than the grid point of a climate model and with much finer detail than a seasonal average. For example, adaptation efforts might require projections for advanced climate metrics such as extreme rain frequency, dry spell length, rainfall distribution over the season, maximum wind gusts from storms, and many more. These quantities are not simulated realistically by climate models, especially where storm organization is key, and their change under enhanced GHG conditions is not quantitatively constrained by theory.

The task ahead for the climate science community, then, is to create reliable projections for spatial scales and physical quantities that are neither resolved by current climate models nor, especially in the case of Africa, well observed. This goal can be met, but must be approached from several angles. One powerful tool is the dynamical downscaling of GCMs by high-resolution models run on large regional domains (Kendon et al., 2017). Another is advanced techniques for statistical downscaling that link observed localized phenomena to characteristics of the large-scale environment (Lee, Tippett, Sobel, & Camargo, 2018; Pinto et al., 2018; Trapp et al., 2007). Yet, these tools should be used with caution, as they can only add value to existing projections if the latter are believable to begin with (Maraun et al., 2017). This will require better global climate models and better observations to constrain them. Fortunately, the international research community is mobilized in ongoing observational and modeling efforts (Dinku et al., 2017; FCFA, 2017; GFDRR, 2015; James et al., 2018; Washington et al., 2012) that have the potential to close our knowledge gaps and further reduce uncertainties in projections. In the meantime, new approaches for the co-production of climate knowledge by scientists and users are coming into focus (Bhave, Conway, & Dessai, 2018; Haasnoot, van t Klooster, & van Alphen, 2018; Kalra et al., 2014; Shepherd et al., 2018; Vincent, Daly, Scannell, & Leathes, 2018) and promise a way forward in planning for adaptation under deep uncertainty.

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## CONFLICT OF INTEREST

The author has declared no conflicts of interest for this article.

## ENDNOTES

[1] The ITCZ has been defined in the literature in many ways (see the discussion in Nicholson, 2018). Here we use the term to refer to the zonal mean tropical precipitation and we characterize its position as the latitude of the precipitation centroid (Bischoff & Schneider, 2014; Donohoe, Marshall, Ferreira, & Mcgee, 2013).

[2] A Mediterranean source for moisture is also found when moisture sources are calculated a posteriori from reanalyses, but this is possibly an artifact of the back trajectory method in cases where rainfall is caused by convergence at low levels along a line between humid and arid air. Paul Dirmeyer, personal communication.

[3] We consider the two together because reduced leaf cover and dry soils have qualitatively similar effects: they cause increases in albedo, but decreases in evapotranspiration and a net warming of surface temperature.

[4] Most simulations also include the history of solar output and volcanic eruptions, but the effect of such natural forcings is not considered here. The general understanding is that solar variability has had little impact on the surface climate, and that volcanic eruptions have tended to decrease monsoon rainfall in general, and in the Sahel in particular (Haywood et al., 2013; Iles & Hegerl, 2014).

[5] Hence, this mode of variability is referred to as the Atlantic Multi-decadal Variability or Atlantic Multi-decadal Oscillation.

[6] The "direct" path is also known in the literature as "fast" response because it emerges within months in simulations that instantaneously quadruple $CO_2$, the indirect path is known also as the "slow" response because it requires that the oceans come in equilibrium with the forcing, as heat penetrates first into the surface mixed layer and finally into the abyssal depths.

[7] Technically, from whether the convective parameterization requires very deep vertical motion to produce much rainfall, or if it can do with shallower ascent (Hill et al., 2017).

[8] The literature on emerging constraints provides some important refinement to our assessment of model performance with respect to climate sensitivity, but little progress has been made in translating these insights to the problem of regional climate change (Xie et al., 2015).

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