Rainfall Trends in the African Sahel: characteristics, processes, and causes.

Michela Biasutti*

Article Type:

Advanced Review

Abstract

Rainfall variability in the Sahel is dynamically linked to the global Hadley cell and to the regional monsoon circulation and thus is susceptible to forcings from remote oceans and regional land-sea contrast alike. Warming of the global oceans increases 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 the African Easterly Jet and allows for the organization and intensification of convective disturbances. These processes can explain the observed interannual to multi-decadal variability.

Anomalies in the global sea surface temperature were the dominant forcing of the widespread drought of the 1970s and 1980s. Recently, 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. Sub-seasonal and sub-regional differences in rainfall trends are a simulated response to increased greenhouse gases, suggesting that recent trends might be, in part, anthropogenic.

While uncertainty in future projections remains, confidence in future projections is enhanced by the recognition that the large scale drivers of atmospheric circulations that have been shown to significantly impact rainfall in the Sahel are well resolved by current climate models. A combination of new knowledge from on-going observational and modeling efforts and of new approaches in planning for adaptation under uncertainty can provide a valuable way forward for climate scientists and policy makers alike.

*Lamont-Doherty Earth Observatory of Columbia University

GRAPHICAL TABLE OF CONTENTS

Figure 1: Intense storms and aridity shape life in the Sahel. Greenhouse gases and warming oceans are forcing an even more extreme climate ahead. ©Franoise GUICHARD/Laurent KERGOAT/CNRS Photothque

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 south of the Sahara desert to just north of the tropical forests (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 and 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.

Annual mean rainfall decreases from more than 800 mm in the south to less than 200 mm in the north and determines natural land cover type 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 and minimum 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 at seasonal and intraseasonal time scales and for reliable long-term projections of its changes under global warming. A confident grasp of the mechanisms of rainfall variability at different time scales must underpin these efforts and this review summarizes our current understanding of such mechanisms and points out sources of persistent uncertainty.

Sahel rainfall is considered a facet of the global monsoon (Wang & Ding, 2008), and the wind that converges and ascends in the African rain band is considered part of the planetary Hadley circulation that exports energy from regions of net energy input (the warm tropics) to regions of net energy output (the higher latitudes) (Biasutti et al., 2018b). As such, we expect that rainfall in the Sahel will respond to external forcings even if they are applied to remote regions, as the entire atmosphere rearranges itself to conserve global energy and momentum (Schneider, Bischoff, & Haug, 2014).

Yet, the seasonal, continental rainfall is the aggregate of relatively short-lived (a few hours), small-scale (about 100km in diameter) convective features (Mesoscale Convective Systems, or MCSs). 70–90% of the annual precipitation (the smaller percentage in the southern –sudanian– zone) in West Africa is produced by MCSs, and in particular by fast-moving squall lines and, less frequently, larger Mesoscale Convective Complexes (Mathon, Laurent, & Lebel, 2002; Fink, Vincent, & Ermert, 2006). Seasonal rainfall totals are thus the product of the number and duration of these rain-delivering systems (the frequency of rainfall) and their average rainfall rate (the intensity of rainfall) and understanding the total requires understanding the parts. Knowledge of the dynamics of rain-bearing disturbances leads us to recognize how continental-scale variability, therefore, also ought to respond to regional forcings that are unimportant for the strength of the Hadley (i.e. planetary, moist, deep) circulation. These are the processes that affect the surface gradients in surface temperature and turbulent heat (Cook, 1999; Wu et al., 2009); that give rise to a dry shallow meridional circulation converging into the low-level Inter-Tropical Front (ITF) and resulting into the African Easterly Jet (AEJ) (Grist & Nicholson, 2001); and thus that set the environment in which organized disturbances are triggered and grow.

Wind shear is a key source of organization for convective systems (Houze, 2004) and indeed most squall lines are associated with the presence of the AEJ, their tracks shifting north and south over West Africa in association with the jet's monthly migration (Mathon et al., 2002; Fink & Reiner, 2003). In about 40% of cases, convection is initially organized by low-level synoptic disturbances of the jet called African Easterly Waves (AEW), which grow feeding off the energy of the jet's vertical and horizontal shear. The AEWs modulate the thermodynamic and low-level wind profiles (they provide northward moisture transport between the trough and ridge and enhance the lower-tropospheric vertical wind shear ahead of the trough) thus making the triggering and organization of squall lines more likely. AEWs might also be especially effective in creating intense storms. While Fink and Reiner (2003) note that AEW-forced squall lines "exhibit no extraordinary characteristics (lifetime, propagation speed, size, and rain rate)", 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 and their breaking into meso-vortices.

Finally, we ought to consider how coupling between atmosphere, land, and vegetation can modulate the variability of rainfall at the regional and seasonal scale (Xue, Boone, & Taylor, 2012). Changes in vegetation, soil moisture, and dust change the radiation budget of the surface and of the atmosphere and can affect moisture convergence and recycling (Charney, 1975; Zeng, Neelin, Lau, & Tucker, 1999; Yoshioka et al., 2007; C. M. Taylor & Lebel, 1998; C. M. Taylor et al., 2011). These processes have been shown to matter in observation at the local scale and in sensitivity experiments, but it is unclear if the magnitude of their variability at decadal timescales has been enough to substantially affect rainfall at such scale.

In the rest of this paper, we will review past, current, and projected changes in Sahel rainfall and we will connect them to the mechanisms and drivers highlighted above. In Section1 we summarize observations of rainfall variability in the 20th century. We focus on interannual variations and on the drought decades (the 1970s and 1980s) and on the dominant influence of SST on seasonal mean anomalies. In Section 2 we zoom in on the most recent decades and assess trends in the rainfall distribution across the rainy season. We explain such trends in terms of the dynamics of intense rainfall events and the influences of external drivers on storm environments. In Section 3 we connect past and current trends to changing anthropogenic forcings: emissions of aerosols and greenhouse gases and land-use changes. In Section 4 we conclude with a cautionary view of how to make practical use of our current understanding of Sahel rainfall variability. We appraise the reliability of consensus projections in view of systematic model biases and simplifications and we suggest how to combine plausible global changes with a more robust knowledge of mechanisms of regional variability in oder to guide policy decisions in the presence of uncertainty and risk.

1 Droughts in the 20th century

In the course of the 20th century, variability in seasonal rainfall totals was large and coherent over much of the Sahel (Figure 1).

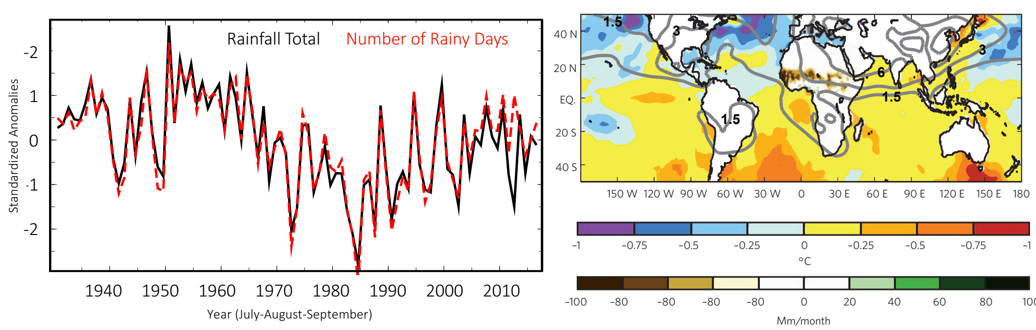

Figure 1: Observed variability in Sahel rainfall. Left: summer-mean (July to September) standardized anomalies in rainfall totals (black solid line) and number of rainy days (blue dashed line) averaged over the region 10°N - 20°N and 20°W - 30°E (from the University of East Anglia Climate Research Unit gridded dataset, TS4.1). Right: Linear trend in summer-mean rainfall between 1940 and 1985 (brown and green hues) and in annual-mean sea surface temperatures over the same period (blue and orange hues). Grey contour lines indicate the corresponding epochal changes in aerosol burden (details in Biasutti, 2011).

The first part of the record shows a predominance of anomalously wet years and decades, followed by a decline in seasonal rainfall totals during the later half of the 20th century, with overall low rainfall decades punctuated by devastating short-term droughts such as those of 1972 and 1983-1984. The map of the multi-decadal rainfall trend highlights the continental scale of long-term climate change in the Sahel.

The cause of the 20th century droughts have 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 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 lead 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., 2016), 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 sidebar). On the other hand, progressively sophisticated computer models of the general circulation of the atmosphere first simulated a decrease in Sahel rainfall when forced with the pattern of the global ocean temperature anomalies of the 70s and 80s (Folland, Palmer, & Parker, 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 Sahel rainfall (the pacing, although not necessarily the full magnitude) has been the variability of SST (see Figure 1), while the potential role of natural soil and vegetation processes has been to amplify the remotely-driven anomalies (Zeng et al., 1999; Giannini et al., 2003; Kucharski, Zeng, & Kalnay, 2012).

At interannual time scales, oceanic variability is dominated by the El Niño Southern Oscillation in the Eastern Pacific. During an El Niño the upwelling of cold deep water declines in the equatorial East Pacific, the surface temperature warms, tropical rainfall extends towards the warmer water, and the troposphere warms up in the entire tropical band. All else being equal, warm temperature anomalies at upper-level would reduce the instability of the air column above the Sahel and dampen rain-producing moist convection, causing drought (Rowell, 2001; Giannini, Biasutti, Held, & Sobel, 2008). Sometimes all else is not equal, and regional circulation changes also occur and have the potential to reduce or overpower the anomalies produced by El Niño (Rodríguez-Fonseca et al., 2015).

The pattern of SST anomalies associated with decade-long droughts in the Sahel is not as uniquely associated with a well-known mode of variability of the ocean, and has lent itself to be interpreted in different ways by different researchers. Both early work (Folland et al., 1986) and recent literature (Hwang, Frierson, & Kang, 2013; Schneider et al., 2014) have emphasized the importance of the inter-hemispheric SST gradient. In this view, when anomalous heat warms one hemisphere, it also triggers a reorganization of the tropical circulation (to partially offset the heat anomaly) that implies a shift of the zonal mean confluence of the Hadley cells towards the warmer hemisphere. The end result is that both peak surface temperature (or, more precisely the boundary-layer moist enthalpy) and the rainfall band shift towards the heated hemisphere. Thus, an anomalously warmer northern hemisphere is associated with a northward shift of the ITCZ and a wetter Sahel while a colder northern hemisphere is associated with a drier Sahel (Figure 1).

Other studies have gone past this diagnostic relationship to connect 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, assuming that the tropics are close to moist neutrality and noting that warmer moist adiabats are more stable, one can surmise that any pattern of warmer than normal tropical SST would lead to more stable tropics and an upped ante for convection (Chou & Neelin, 2004; Giannini et al., 2008; Giannini, 2010).

Giannini et al. (2013) have suggested that positive rainfall anomalies in the Sahel ensue when warm temperature in the subtropical 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 Atlantic controls moisture supply (and controls rainfall accumulation through its intensity). 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)[1]. 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, 2016a).

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 dilute the energy available for convection). Both processes influence convective development and can contribute to the strong association between total column water vapor and daily rainfall that is a hallmark of tropical rainfall (Bretherton, Peters, & Back, 2004). In the Sahel, variations in the temperature profile dominate over humidity in modulating the seasonal-scale of the level of free convection and of the occurrence and intensity of deep convection (Kollias, Miller, Johnson, Jensen, & Troyan, 2009). Furthermore, if advective anomalies or the radiative effect of added moisture were to shift the Sahara Heat Low to the north, the resulting shift of the mid-level divergence would allow more rainfall at the latitude of the Sahel (Evan, Flamant, Lavaysse, Kocha, & Saci, 2015; Shekhar & Boos, 2017; Zhai & Boos, 2017) and the changes in the meridional and vertical gradients of temperature would also affect the position and the strength of the AEJ and the degree of convective organization over the Sahel (Laing & Fritsch, 2000; Fink & Reiner, 2003).

Even though regional circulation anomalies are driven by global SST changes, they are

[1] 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

likely amplified by processes that are local to the Sahel, specifically by the fluxes of matter and energy associated with biogeochemical and biophysical vegetation and soil processes. 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; Timm, Köhler, Timmermann, & Menviel, 2010; Mohtadi, Prange, & Steinke, 2016; Pausata, Messori, & Zhang, 2016), but at shorter time-scales it is sufficient to consider moisture and energy feedbacks involving plant function and soil properties[2]. 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.

The traditional view of land moisture feedback focused on moisture recycling: a wet surface can provide more water vapor to fuel more convection and rainfall (Brubaker, Entekhabi, & Eagleson, 1993), thus acting as a positive feedback on rainfall variability. Recent work has emphasized other aspects of the coupling. At the mesoscale, soil moisture heterogeneities play an important role in triggering surface convergence and storm initiation, with rainfall more likely over dry patches (C. M. Taylor, de Jeu, Guichard, Harris, & Dorigo, 2012; C. M. Taylor et al., 2011), but such a negative feedback is limited to the small scale and does not carry over to regional rainfall (Guillod, Orlowsky, Miralles, Teuling, & Seneviratne, 2015; Seneviratne et al., 2010). At the regional scale of the Sahel, 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 African Easterly Jet), leading to complex feedbacks and model-dependent behavior (Berg, Lintner, Findell, & Giannini, 2017b).

2 Recent changes in rainfall characteristics

Observations shows 1984 to be the driest year on record in the Sahel. Rainfall totals trended upwards since then (Dai et al., 2004), fueled by more extensive and intense mesoscale dis-

[2]The biogeochemical feedbacks involving plant emission of radiatively and chemically active compounds can be important for future trends, but not for 20th century variability.

turbances (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 (West, Roncoli, & Ouattara, 2008; Tambo & Abdoulaye, 2012).

Coarse gridded records show that seasonal rainfall totals go hand in hand with the number of wet days during the 20th century but the relationship weakens somewhat in the most recent period, suggesting that variations in rainfall intensity are non-negligible even at the regional and seasonal scale (see Figure 1). Moreover, a growing literature based on high-resolution satellite estimates and daily gauge data has identified trends in extreme rainfall events and in the intraseasonal variability of rainfall, corroborating anecdotal accounts and on-the-ground experiences.

C. M. Taylor et al. (2017), used Infra-Red satellite images to identify storms and found that the most extreme ones tripled over the course of three decades. 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: mid-level dry air intensifies MCSs via enhanced evaporative downdraughts and a stronger jet provides the shear to organize convection (and, possibly, to increase triggering of convection by AEWs). These mechanisms are all directly linked to a warming Sahara, and may be a sign of anthropogenic influence on the characteristics of storms.

A direct assessment of trends in the characteristics of rainfall itself is complicated by the quality of the observations and by the intrinsic noisiness of the record (especially for extreme events). Using satellite-based rainfall datasets 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 towards less frequent intense rainfall, even as total rainfall and rainfall frequency trend towards 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 that 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 40mm threshold) occurrences were compared directly, the station network showed no coherent change, with half the stations indicating increase 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.

3 Past and future anthropogenic trends

Emissions of greenhouse gases and aerosol particles, the byproducts of industrialization, have already warmed the surface temperature of the global ocean and, even more, of land — and are projected to do so even faster in the rest of this century. Given the established evidence that Sahel rainfall responds to anomalies in regional land temperature gradients and in global SST, we can ask what part of that past variability was ultimately driven by 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 CGCMs) or the history of anthropogenic emissions (Earth System Models, ESMs, which simulate the chemical and biological systems that process anthropogenic emissions and calculate the resulting changes in atmospheric composition).[3] Dozens such models exist (K. E. 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 both 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 an indication of the uncertainty of such estimate (noise) — although the estimates of both the signal and the noise are biased in ways not easily quantifiable.

Many studies have established the presence of a forced component in Sahel rainfall; 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 sulphates) in North America and Europe (see Figure 1). These aerosols cause cooling both through their direct scattering of solar radiation away from the surface and through their ability to make clouds brighter and more long-lived, but because they are easily removed by the atmosphere (either by dry deposition or by

[3]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 (Iles & Hegerl, 2014; Haywood, Jones, Bellouin, & Stephenson, 2013)

rainfall), their cooling effect is regional and hemispheric, not global (Myhre, Shindell, Bréon, & Table, 2013). The cooling of the northern hemisphere relative to the southern hemisphere is expected to shift the zonal mean ITCZ to the south (Schneider et al., 2014), and the drying of the Sahel during these decades has indeed been interpreted as part of the ITCZ response to the aerosol forcing (Rotstayn & Lohmann, 2002; Biasutti & Giannini, 2006; Ackerley et al., 2011; Booth, Dunstone, Halloran, Andrews, & Bellouin, 2012; Hwang et al., 2013). 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, either through a change in the deep oceanic circulation (R. 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 (R. Zhang et al., 2013) and the strength of the simulated natural variability in the oceanic meridional circulation (Ba et al., 2014). Going from the attribution of the SST anomalies to the attribution of the Sahel rainfall anomalies introduces another layer of uncertainty: 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, paced by processes that are 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 sulphate emissions in the US and Europe – even though pollution of this kind has increased in Asia over the same period so that global sulphate aerosol forcing has held steady (Myhre et al., 2013). In addition, we also need to consider the forcing by greenhouse gases (GHG), which has increased unabated over this period, and which is believed to force positive rainfall anomalies in the Sahel (Biasutti, 2013).

GHG force rainfall anomalies in the Sahel through forced changes in the pattern of global sea surface temperature and directly, through the increased energy input into the land surface and the atmospheric column. [4] The direct effect of GHGs such as CO2 is to wet the Sahel for all models (Biasutti, 2013), consistent with the interpretation of the monsoon as a facet of the energetically direct tropical circulation (Biasutti et al., 2018a). Mechanistically, the positive response has been explained as the consequence of warming over the Sahara and strengthening the monsoonal circulation in what amounts to an intensification of the seasonal cycle dynamics (Haarsma, Selten, Weber, & Kliphuis, 2005; Biasutti, Sobel, & Camargo, 2009). 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 (Shekhar & Boos, 2017; Gaetani et al., 2016).

The anomalies forced on the Sahel by the CO2-induced changes in global sea surface temperature are less robust across models, because of both 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, Bader, & Matei, 2016b), relative to the overall warming) and different atmospheric sensitivity to the same oceanic anomalies (Held, Delworth, Lu, Findell, & Knutson, 2005; Biasutti, Held, Sobel, & Giannini, 2008; Hill, Ming, Held, & Zhao, 2017; Park et al., 2015; Gaetani et al., 2016). Different atmospheric sensitivities to overall warming are likely to stem from how the models produce convective rainfall given a certain large scale atmospheric environment (specifically, from whether a model requires very deep vertical motion to produce much rainfall, or if it can do with shallower ascent, (Hill et al., 2017)). Different responses to the same SST patterns are not easily explained (Rowell, Senior, Vellinga, & Graham, 2015). Nevertheless, there is qualitative agreement that warming of the global oceans would lead, by itself, to dry anomalies in the Sahel (Biasutti, 2013).

[4] The latter is known in the literature as the "fast response" because it emerges within months in simulations that instantaneously quadruple CO2, the former is known as the "slow response" because it requires that the ocean come in equilibrium with the forcing, as heat penetrates first into the surface mixed layer and finally into the abyssal depths.)

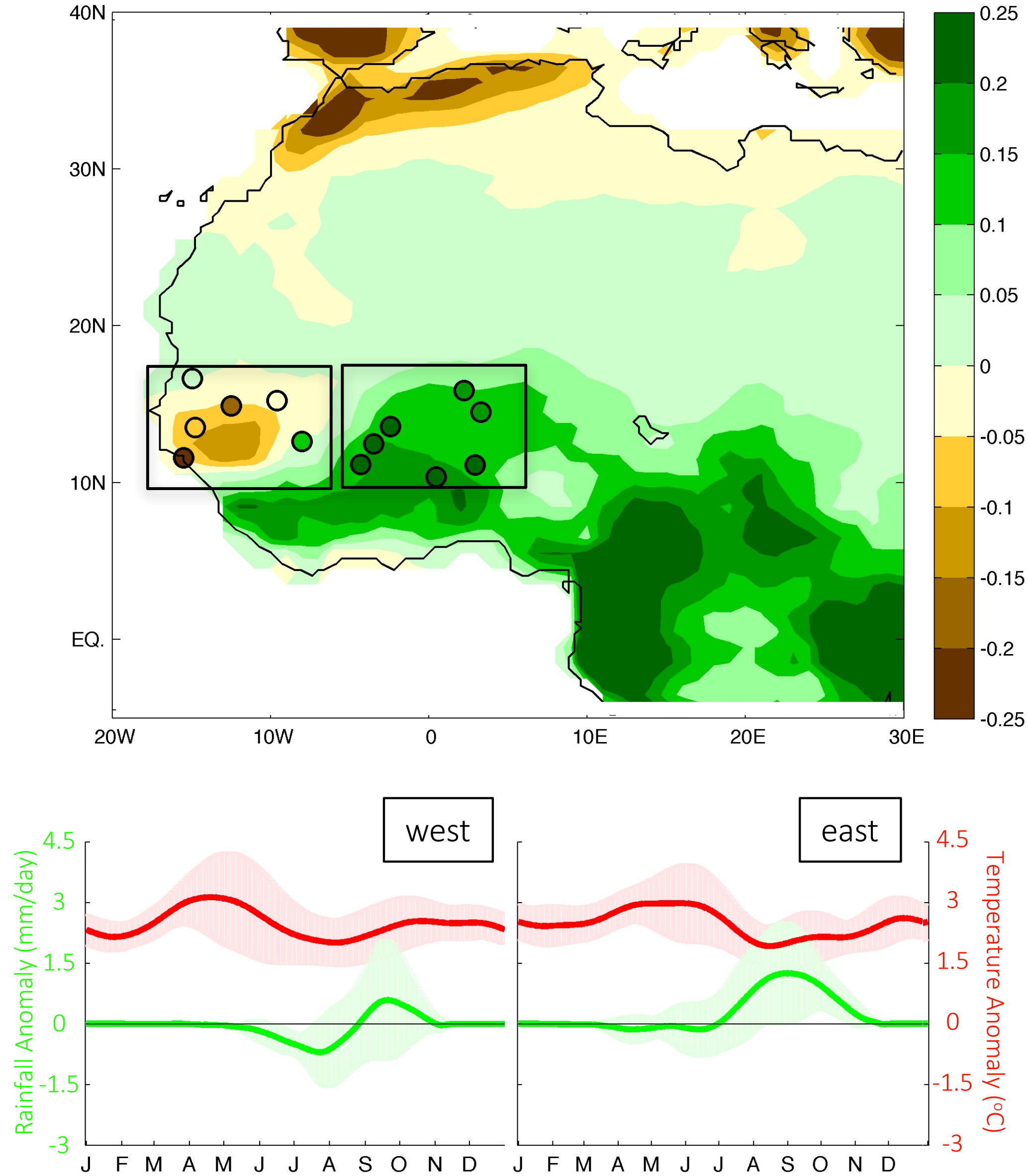

Figure 2: Projected changes in Sahel rainfall. Top: Multi-model averaged, annual mean rainfall anomalies (in mm per day) between future and past. Field values are the anomalies in the raw model output. Filled circles are anomalies in the bias-corrected output. The boxes indicate West and East locations. Bottom: Smoothed daily anomalies in rainfall (mm/day, green) and temperature (°C, red) averaged over western (left) and eastern (right) locations. The solid line is the multi-model mean, the shading represents one standard deviation scatter. (details in Guan et al., 2017).

Detection of a signature of CO2 forcing in recent decades might be aided by the fact that scenario simulations produce zonal and seasonal asymmetries in the rainfall response: the annual mean positive anomalies do not extend all the way to the westernmost Sahel and they arise as a compensation between early season drying and late season wetting (see Figure 2 and Biasutti & Sobel, 2009; Biasutti, 2013). The zonal asymmetry likely derives from the influence of the Sahara Heat Low. Because the low is not zonally symmetric but it 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 CO2 or through the effect of warm and moist advection from a warmer ocean have the same effect on the position and strength of the Low, thus the asymmetry between the eastern and western Sahel rainfall anomalies is compounded in the full response to CO2 (Gaetani et al., 2016).

The seasonality of the response to CO2 has not been fully explained yet. Qualitatively, we think of the early rainy season as a time when the conditions for convective instability are rarely met — so that an increase in global atmospheric stability exacerbates the inhibition (Chou & Neelin, 2004; Lintner & Neelin, 2007; Giannini, 2010) — and the core rainy season as a time when ascent is always possible — so that an increase in global specific humidity intensifies rainfall (Held & Soden, 2006; Huang, Xie, Hu, Huang, & Huang, 2013). In this view, the role of local greenhouse gases forcing is to provide the energy necessary to overcome the inhibition and thus to bring the Sahel from a dry to a wet regime (Giannini, 2010; Seth et al., 2013). A more complete explanation needs to incorporate the regional circulation that provides the moisture for rainfall, and thus would also account for the modification to the shallow circulation and the cyclonic circulation that are associated with direct CO2 forcing of the north African continent. It should also be noted that soil moisture feedbacks can change the seasonal contrast in rainfall anomalies and introduce another source of model uncertainty: (Berg, Lintner, Findell, & Giannini, 2017a) has shown that, in some models, surface evaporative cooling after rain acts as a negative feedback in the early monsoon season and as a positive feedback in the core and late monsoon season.

The fingerprint of CO2 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 CO2-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 emergence of a global warming signal. Nevertheless, we note that some features of the expected pattern of CO2-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 CO2-forced simulations. In contrast, W. 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 dataset in the latter region suggests caution. 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, the spatial and seasonal patterns of recent rainfall anomalies suggests that CO2 forcing has been contributing to the observed recovery.

Moreover, one robust consequence of global warming is the increase of mean and extreme rainfall intensity (Sillmann, Kharin, Zwiers, Zhang, & Bronaugh, 2013; O'Gorman & Schneider, 2009) and the increase of Sahel rainfall since the 1980s is due in non-negligible 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, 2017) and, as pointed out by C. M. Taylor et al. (2017), this would also imply a robust effect of GHG on the occurrence of intense rainfall.

Finally, we address the possibility that 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 (Hagos et al., 2014; Boone et al., 2016) 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 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., 2016), 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 and are expected to play a similarly minor role in future climate change.

4 Discussion and Conclusions

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 disagreement in climate projections? And how should we handle model consensus when all models have common systematic biases?

How to handle model disagreement in climate projections?

Climate models are routinely validated against observations of the global climate during the last few decades, for which our observational estimates are sufficiently well constrained, but there is no single metric by which we can rank models from worst to best (Pierce, Barnett, Santer, & Gleckler, 2009; Gleckler, Taylor, & Doutriaux, 2008). 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[5]. 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, but 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. Observed teleconnections and theoretical arguments are then used to provide a linkage 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 condition 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 — given what we have learned about the mechanisms that have driven Sahel rainfall anomalies so far — we speculate that the relevant storylines would describe the gradient between the global tropics and the northern mid-latitude and be linked to the strength and location of the heat low.

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

At the other end of the uncertainty spectrum is the possibility that the full ensemble of coupled models agree on a specific projection. It is often assumed that model agreement

[5] 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)

means less uncertainty in the prediction and this is a warranted conclusion in those cases in which the simulated response is consistent with established theory. The obvious example is 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.

Some of these common systematic biases have the potential to 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 simulation, contrary to observations. The equatorial warming is also a major feature of future projections. What would it mean for the Sahel if this projection 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 if there were no additional warming in the equatorial Pacific, because of a lesser increase in stability and a more pronounced relative warming in the Atlantic and Mediterranean.

Second, the development and organization of rain system over land is not well represented by current convective parameterization, so that the diurnal cycle , the temporal coherence, and the profile of time-mean ascent of rainfall have common systematic biases in GCMs (Covey et al., 2016; Roehrig, Bouniol, Guichard, Hourdin, & Redelsperger, 2013). With enhanced bottom-heaviness of the ascent profile, Sahel rainfall would probably be less susceptible to increases in stability driven by the tropical warming (Hill et al., 2017; Giannini et al., 2013), wetting even more in response to GHG. The effect of other systematic biases in convection are less amenable to speculation, as they depend on the interaction of clouds and radiations. Convection resolving simulations are coming online and will provide further guidance (Stratton et al., 2018).

Conclusions

Rainfall in the Sahel has undergone profound changes during the observational record, both in seasonal amounts and in intra-seasonal characteristics. Decades of research in this area have led to a confident understanding that these aspects of rainfall variability can be explained as responses to anomalies in the atmospheric circulation that are planetary or regional in scale and that are mostly driven from outside the Sahel — 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 are large scale (and thus well resolved by the current generation of climate models) lends some confidence in the future projections. 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. The climate community is mobilized in on-going observational and modeling efforts that have the potential to further reduce these uncertainties. In the meanwhile, new approaches in planning for adaptation under deep uncertainty can already provide a valuable way forward for policy makers.

SIDEBAR: Drought, Desertification, and Resilience

On the heels of the "Great Drought" of 1968-1973 , the United Nations General Assembly called for international co-operation 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 to 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 and whose 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, socio-economic 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 (Reynolds et al., 2007; Mortimore, 2010). Still, loss of soil fertility and biodiversity remain widespread problems and, 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).

SIDEBAR: Heat, Aridity, and Yields in a High CO_2 World

Crop models driven by idealized (Sultan et al., 2013) or projected (Sultan et al., 2014) changes in atmospheric drivers (temperature, rainfall, radiation) simulate a decline in grain yields across the entire Sahel due primarily to increasing temperature and only secondarily through changes in rainfall. But the effect on vegetation of warming has itself generally been interpreted as increased water stress, through an increase in water vapor deficit that is a robust consequence of 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.

But high CO_2 concentration affects the physiological behavior of plants: CO2 fertilization increases vegetation and leaf area but at the same time reduces stomata opening. New research has shown that the net effect is to limit transpiration. In regions where evapotranspiration is moisture-limited, this leads to additional warming and drying of the near-surface atmosphere. Thus, off-line calculations of aridity double count the effect of warming and overestimate 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 (Wieder, Cleveland, Smith, & Todd-Brown, 2015; Berg, Sheffield, & Milly, 2017).

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 CO2 on agricultural productivity.

References

Ackerley, D., Booth, B. B. B., Knight, S. H. E., Highwood, E. J., Frame, D. J., Allen, M. R., & Rowell, D. P. (2011, October). Sensitivity of Twentieth-Century Sahel Rainfall to Sulfate Aerosol and CO 2Forcing. *Journal of Climate*, *24*(19), 4999–5014.

Ali, A., & Lebel, T. (2009, October). The Sahelian standardized rainfall index revisited. *International Journal of Climatology*, *29*(12), 1705–1714.

Ba, J., Keenlyside, N. S., Latif, M., Park, W., Ding, H., Lohmann, K., … Volodin, E. (2014, January). A multi-model comparison of Atlantic multidecadal variability. *Climate Dynamics*, *43*(9-10), 2333–2348.

Bader, J., & Latif, M. (2003). The impact of decadal-scale Indian Ocean sea surface temperature anomalies on Sahelian rainfall and the North Atlantic Oscillation. *Geophys Res Lett*, *30*(22), 2169.

Bell, M. A., & Lamb, P. J. (2006, October). Integration of Weather System Variability to Multidecadal Regional Climate Change: The West African Sudan–Sahel Zone, 1951–98. *Journal of Climate*, *19*(20), 5343–5365.

Berg, A., Lintner, B., Findell, K., & Giannini, A. (2017a, March). Soil Moisture Influence on Seasonality and Large-Scale Circulation in Simulations of the West African Monsoon. *Journal of Climate*, *30*(7), 2295–2317.

Berg, A., Lintner, B. R., Findell, K., & Giannini, A. (2017b, June). Uncertain soil moisture feedbacks in model projections of Sahel precipitation. *Geophysical Research Letters*, *44*(12), 6124–6133.

Berg, A., & Sheffield, J. (2018, April). Climate Change and Drought: the Soil Moisture Perspective. *Current Climate Change Reports*, *4*(2), 180–191.

Berg, A., Sheffield, J., & Milly, P. C. D. (2017, January). Divergent surface and total soil moisture projections under global warming. *Geophysical Research Letters*, *44*(1), 236–244.

Biasutti, M. (2011, June). Atmospheric science: A man-made drought. *Nature Climate Change*, *1*(4), 197–198.

Biasutti, M. (2013, February). Forced Sahel rainfall trends in the CMIP5 archive. *Journal of Geophysical Research*, *118*(4), 1613–1623.

Biasutti, M., & Giannini, A. (2006). Robust Sahel drying in response to late 20th century forcings. *Geophysical Research Letters*, *33*(11), –.

Biasutti, M., Held, I. M., Sobel, A. H., & Giannini, A. (2008). SST forcings and Sahel Rainfall Variability in Simulations of the Twentieth and Twenty-First Centuries. *Journal of Climate*, *21*(14), 3471–3486.

Biasutti, M., & Sobel, A. H. (2009). Delayed seasonal cycle and African monsoon in a warmer climate. *Geophys Res Lett*, *36*, L23707.

Biasutti, M., Sobel, A. H., & Camargo, S. J. (2009). The role of the Sahara Low in summertime Sahel rainfall variability and change in the CMIP3 models. *Journal of Climate*, *22*, 5755–5771.

Biasutti, M., Voigt, A., Boos, W. R., Braconnot, P., Hargreaves, J. C., Harrison, S. P., ... Xie, S.-P. (2018a, June). Global energetics and local physics as drivers of past, present and future monsoons. *Nature Geoscience*, *11*(6), 392–400.

Biasutti, M., Voigt, A., Boos, W. R., Braconnot, P., Hargreaves, J. C., Harrison, S. P., ... Xie, S.-P. (2018b). *An integrated view of monsoons and the ITCZ across time and space scales .*

Boone, A. A., Xue, Y., De Sales, F., Comer, R. E., Hagos, S. M., Mahanama, S., ... Mechoso, C. R. (2016, July). The regional impact of Land-Use Land-cover Change (LULCC) over West Africa from an ensemble of global climate models under the auspices of the WAMME2 project. *Climate Dynamics*, *47*(11), 3547–3573.

Booth, B. B. B., Dunstone, N. J., Halloran, P. R., Andrews, T., & Bellouin, N. (2012, April). Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature*, *484*(7393), 228–232.

Brandt, M., Rasmussen, K., Peñuelas, J., Tian, F., Schurgers, G., Verger, A., … Fensholt, R. (2017, April). Human population growth offsets climate-driven increase in woody vegetation in sub-Saharan Africa. *Nature Ecology & Evolution*, *1*(4), 0081.

Bretherton, C. S., Peters, M. E., & Back, L. E. (2004). Relationships between Water Vapor Path and Precipitation over the Tropical Oceans. *Journal of Climate*, *17*, 1517–1528.

Brubaker, K. L., Entekhabi, D., & Eagleson, P. S. (1993, June). Estimation of Continental Precipitation Recycling. *Journal of Climate*, *6*(6), 1077–1089.

Charney, J. G. (1975). Dynamics of deserts and drought in the Sahel. *Quart. J. Roy. Meteor. Soc, 101, 193*, *101*, 193–202.

Chou, C., & Neelin, J. D. (2004, July). Mechanisms of Global Warming Impacts on Regional Tropical Precipitation*. *Journal of Climate*, *17*(13), 2688–2701.

Clement, A., Bellomo, K., Murphy, L. N., Cane, M., Mauritsen, T., Radel, G., & Stevens, B. (2015, October). The Atlantic Multidecadal Oscillation without a role for ocean circulation. *Science*, *350*(6258), 320–324.

Coats, S., & Karnauskas, K. (2017, October). Are Simulated and Observed Twentieth Century Tropical Pacific Sea Surface Temperature Trends Significant Relative to Internal Variability? *Geophysical Research Letters*, *44*(19), 9928–9937.

Cook, K. H. (1999). Generation of the African Easterly Jet and its role in determining West African Precipitation. *Journal of Climate*, *12*, 1165–1184.

Covey, C., Gleckler, P. J., Doutriaux, C., Williams, D. N., Dai, A., Fasullo, J., … Berg, A. (2016, June). Metrics for the Diurnal Cycle of Precipitation: Toward Routine Benchmarks for Climate Models. *Journal of Climate*, *29*(12), 4461–4471.

Dai, A., Lamb, P. J., Trenberth, K. E., Hulme, M., Jones, P. D., & Xie, P. (2004, August). The recent Sahel drought is real. *International Journal of Climatology*, *24*(11), 1323–1331.

Dardel, C., Kergoat, L., Hiernaux, P., Mougin, E., Grippa, M., & Tucker, C. (2014, January). Re-greening Sahel: 30 years of remote sensing data and field observations (Mali, Niger). *Remote Sensing of Environment*, *140*, 350–364.

Evan, A. T., Flamant, C., Lavaysse, C., Kocha, C., & Saci, A. (2015, January). Water Vapor–Forced Greenhouse Warming over the Sahara Desert and the Recent Recovery from the Sahelian Drought. *Journal of Climate*, *28*(1), 108–123.

Fink, A. H., & Reiner, A. (2003). Spatiotemporal variability of the relation between African Easterly Waves and West African Squall Lines in 1998 and 1999. *Journal of Geophysical Research*, *108*(D11), 199.

Fink, A. H., Vincent, D. G., & Ermert, V. (2006, August). Rainfall Types in the West African Sudanian Zone during the Summer Monsoon 2002. *Mon. Wea. Rev.*, *134*(8), 2143–2164.

Folland, C. K., Palmer, T. N., & Parker, D. E. (1986). Sahel rainfall and worldwide sea temperature, 1901-85. *Nature*, *320*, 602–687.

Gaetani, M., Flamant, C., Bastin, S., Janicot, S., Lavaysse, C., Hourdin, F., … Bony, S. (2016, April). West African monsoon dynamics and precipitation: the competition between global SST warming and CO¡Subscript¿2¡/Subscript¿ increase in CMIP5 idealized simulations. *Climate Dynamics*, *48*(3-4), 1353–1373.

Giannini, A. (2010). Mechanisms of Climate Change in the Semiarid African Sahel: The Local View. *Journal of Climate*, *23*(3), 743–756.

Giannini, A., Biasutti, M., Held, I. M., & Sobel, A. H. (2008). A global perspective on African climate. *Climatic Change*, *90*(4), 359–383.

Giannini, A., Salack, S., Lodoun, T., Ali, A., Gaye, A. T., & Ndiaye, O. (2013, April). A unifying view of climate change in the Sahel linking intra-seasonal, interannual and longer time scales. *Environmental Research Letters*, *8*(2), 024010.

Giannini, A., Saravanan, R., & Chang, P. (2003). Oceanic forcing of Sahel rainfall on interannual to interdecadal time scale. *Science*, *302*, 1027–1030.

Gleckler, P., Taylor, K., & Doutriaux, C. (2008). Performance metrics for climate models. *J. Geophys. Res*, *113*.

Grist, J. P., & Nicholson, S. (2001). A study of the dynamic factors influencing the rainfall variability in the West African Sahel. *Journal of Climate*, *14*, 1337–1359.

Guan, K., Sultan, B., Biasutti, M., Baron, C., & Lobell, D. B. (2017, January). Assessing climate adaptation options and uncertainties for cereal systems in West Africa. *Agricultural and Forest Meteorology*, *232*, 291–305.

Guillod, B. P., Orlowsky, B., Miralles, D. G., Teuling, A. J., & Seneviratne, S. I. (2015, March). Reconciling spatial and temporal soil moisture effects on afternoon rainfall. *Nature Communications*, *6*(1), 6443.

Haarsma, R. J., Selten, F. M., Weber, S. L., & Kliphuis, M. (2005). Sahel rainfall variability and response to greenhouse warming. *Geophys Res Lett*, *32*, L17702.

Hagos, S. M., & Cook, K. H. (2008). Ocean warming and late-twentieth-century Sahel drought and recovery. *Journal of Climate*, *21*(15), 3797–3814.

Hagos, S. M., Leung, L. R., Xue, Y., Boone, A., Sales, F., Neupane, N., … Yoon, J.-H. (2014, February). Assessment of uncertainties in the response of the African monsoon precipitation to land use change simulated by a regional model. *Climate Dynamics*.

Haywood, J. M., Jones, A., Bellouin, N., & Stephenson, D. (2013, July). Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. *Nature Climate Change*, *3*(7), 660–665.

Held, I. M., Delworth, T., Lu, J., Findell, K. L., & Knutson, T. (2005). Simulation of Sahel Drought in the 20th and 21st Centuries. *Proc. Natl. Acad. Sci.*, *102*(50), 17891–17896.

Held, I. M., & Soden, B. J. (2006). Robust responses of the hydrological cycle to global warming. *Journal of Climate*, *19*(21), 5686–5699.

Herrmann, S., Anyamba, A., & Tucker, C. (2005). Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. *Global Environmental Change Part A*, *15*(4), 394–404.

Herrmann, S., & Hutchinson, C. F. (2005). The changing contexts of the desertification debate. *Journal of Arid Environments*, *63*, 538–555.

Hill, S. A., Ming, Y., Held, I. M., & Zhao, M. (2017, August). A Moist Static Energy Budget–Based Analysis of the Sahel Rainfall Response to Uniform Oceanic Warming. *Journal of Climate*, *30*(15), 5637–5660.

Houze, R. A. (2004). Mesoscale convective systems. *Reviews of Geophysics,*, *42*(4), RG4003.

Huang, P., Xie, S.-P., Hu, K., Huang, G., & Huang, R. (2013, May). Patterns of the seasonal response of tropical rainfall to global warming. *Nature Geoscience*, *6*(5), 357–361.

Hwang, Y.-T., Frierson, D. M. W., & Kang, S. M. (2013, June). Anthropogenic sulfate aerosol and the southward shift of tropical precipitation in the late 20th century. *Geophysical Research Letters*, *40*(11), 2845–2850.

Iles, C. E., & Hegerl, G. C. (2014, October). The global precipitation response to volcanic eruptions in the CMIP5 models. *Environmental Research Letters*, *9*(10), 104012.

Kendon, E. J., Jones, R. G., Kjellström, E., & Murphy, J. M. (2010, December). Using and Designing GCM–RCM Ensemble Regional Climate Projections. *Journal of Climate*, *23*(24), 6485–6503.

Keys, P. W., Barnes, E. A., van der Ent, R. J., & Gordon, L. J. (2014). Variability of moisture recycling using a precipitationshed framework. *Hydrology and Earth System Sciences*, *18*(10), 3937–3950.

Kollias, P., Miller, M. A., Johnson, K. L., Jensen, M. P., & Troyan, D. T. (2009, June). Cloud, thermodynamic, and precipitation observations in West Africa during 2006. *Journal of Geophysical Research: Atmospheres (1984–2012)*, *114*(D13), 2760.

Kucharski, F., Zeng, N., & Kalnay, E. (2012, May). A further assessment of vegetation feedback on decadal Sahel rainfall variability. *Climate Dynamics*.

Kutzbach, J., Bonan, G. B., Foley, J., & Harrison, S. P. (1996, December). Vegetation and soil feedbacks on the response of the African monsoon to orbital forcing in the early to middle Holocene. *Nature*, *384*(6610), 623–626.

Lafore, J. p., Beucher, F., Peyrillé, P., Niang, A. D., Chapelon, N., Bouniol, D., ... Vischel, T. (2017, November). A multi-scale analysis of the extreme rain event of Ouagadougou in 2009. *Quarterly Journal of the Royal Meteorological Society*, *143*(709), 3094–3109.

Laing, A. G., & Fritsch, J. M. (2000). The large-scale environments of the global populations of mesoscale convective complexes. *Monthly Weather Review*, *128*(8), 2756–2776.

Lavaysse, C., Flamant, C., & Janicot, S. (2010, August). Regional-scale convection patterns during strong and weak phases of the Saharan heat low. *Atmospheric Science Letters*, *11*(4), 255–264.

Lebel, T., & Ali, A. (2009, August). Recent trends in the Central and Western Sahel rainfall regime (1990–2007). *Journal of Hydrology*, *375*(1-2), 52–64.

Li, G., & Xie, S.-P. (2014, February). Tropical Biases in CMIP5 Multimodel Ensemble: The Excessive Equatorial Pacific Cold Tongue and Double ITCZ Problems*. *Journal of Climate*, *27*(4), 1765–1780.

Lintner, B. R., & Neelin, J. (2007, March). A prototype for convective margin shifts.

Geophysical Research Letters, *34*(5), L05812.

Liu, Y., & Chiang, J. (2012, May). Coordinated Abrupt Weakening of the Eurasian and North African Monsoons in the 1960s and Links to Extratropical North Atlantic Cooling. *Journal of Climate*, *25*(10), 3532–3548.

Lodoun, T., Giannini, A., Traoré, P. S., Somé, L., Sanon, M., Vaksmann, M., & Rasolodimby, J. M. (2013, January). Changes in seasonal descriptors of precipitation in Burkina Faso associated with late 20th century drought and recovery in West Africa. *Environmental Development*, *5*, 96–108.

Maestre, F. T., Eldridge, D. J., Soliveres, S., Kéfi, S., Delgado-Baquerizo, M., Bowker, M. A., … Berdugo, M. (2016, November). Structure and Functioning of Dryland Ecosystems in a Changing World. *Annual Review of Ecology, Evolution, and Systematics*, *47*(1), 215–237.

Mathon, V., Laurent, H., & Lebel, T. (2002). Mesoscale convective system rainfall in the Sahel. *Journal of Applied Meteorology*, *41*(11), 1081–1092.

Mohtadi, M., Prange, M., & Steinke, S. (2016, May). Palaeoclimatic insights into forcing and response of monsoon rainfall. *Nature*, *533*(7602), 191–199.

Mortimore, M. (2010). Adapting to drought in the Sahel: lessons for climate change. *WIREs Climate Change*, *1*, 134–143.

Myhre, G., Shindell, D., Bréon, F. M., & Table, W. C. (2013). Anthropogenic and Natural Radiative Forcing. In *Climate change 2013 the physical science basis. contribution of working group i to the fifth assessment report of the intergovernmental panel on climate change.* Cambridge University Press.

Nicholson, S. (2005, November). On the question of the "recovery" of the rains in the West African Sahel. *Journal of Arid Environments*, *63*(3), 615–641.

Odoulami, R. C., & Akinsanola, A. A. (2017, September). Recent assessment of West African summer monsoon daily rainfall trends. *Weather*, *35*(3), 1107.

O'Gorman, P. A., & Schneider, T. (2009, September). The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. *Proc. Natl. Acad. Sci.*, *106*(35), 14773–14777.

Panthou, G., Vischel, T., & Lebel, T. (2014, March). Recent trends in the regime of extreme rainfall in the Central Sahel. *International Journal of Climatology*, *34*(15), 3998–4006.

Park, J.-Y., Bader, J., & Matei, D. (2015, January). Northern-hemispheric differential warming is the key to understanding the discrepancies in the projected Sahel rainfall. *Nature Communications*, *6*(1), 5985.

Park, J.-Y., Bader, J., & Matei, D. (2016a). Anthropogenic Mediterranean warming essential driver for present and future Sahel rainfall. *Nature Climate Change*.

Park, J.-Y., Bader, J., & Matei, D. (2016b, October). Anthropogenic Mediterranean warming essential driver for present and future Sahel rainfall. *Nature Climate Change*, *6*(10), 941–945.

Pausata, F. S. R., Messori, G., & Zhang, Q. (2016, January). Impacts of dust reduction on the northward expansion of the African monsoon during the Green Sahara period. *Earth and Planetary Science Letters*, *434*, 298–307.

Pierce, D. W., Barnett, T. P., Santer, B. D., & Gleckler, P. J. (2009, May). Selecting global climate models for regional climate change studies. *Proceedings of the National Academy of Sciences*, *106*(21), pnas.0900094106–8446.

Reynolds, J. F., Smith, D. M. S., Lambin, E. F., Turner, B. L., Mortimore, M., Batterbury, S. P. J., … Walker, B. (2007, May). Global Desertification: Building a Science for Dryland Development. *Science*, *316*(5826), 847–851.

Rodríguez-Fonseca, B., Mohino, E., Mechoso, C. R., Caminade, C., Biasutti, M., Gaetani, M., … Voldoire, A. (2015, May). Variability and Predictability of West African Droughts: A Review on the Role of Sea Surface Temperature Anomalies. *Journal of Climate*, *28*(10), 4034–4060.

Roehrig, R., Bouniol, D., Guichard, F., Hourdin, F., & Redelsperger, J.-L. (2013, September). The Present and Future of the West African Monsoon: A Process-Oriented Assessment of CMIP5 Simulations along the AMMA Transect. *Journal of Climate*, *26*(17), 6471–6505.

Rotstayn, L. D., & Lohmann, U. (2002). Tropical Rainfall Trends and the Indirect Aerosol Effect. *Journal of Climate*, *15*, 2103–2116.

Rowell, D. P. (2001, July). Teleconnections between the tropical Pacific and the Sahel. *Quarterly Journal of the Royal Meteorological Society*, *127*(575), 1683–1706.

Rowell, D. P., Senior, C. A., Vellinga, M., & Graham, R. J. (2015, November). Can climate projection uncertainty be constrained over Africa using metrics of contemporary performance? *Climatic Change*, *134*(4), 621–633.

Salack, S., Giannini, A., Diakhaté, M., Gaye, A. T., & Muller, B. (2013, February). Oceanic influence on the sub-seasonal to interannual timing and frequency of extreme dry spells over the West African Sahel. *Climate Dynamics*.

Salack, S., Saley, I. A., Lawson, N. Z., Zabré, I., & Daku, E. K. (2018, June). Scales for rating heavy rainfall events in the West African Sahel. *Weather and Climate Extremes*.

Sanogo, S., Fink, A. H., Omotosho, J. A., Ba, A., Redl, R., & Ermert, V. (2015, December). Spatio-temporal characteristics of the recent rainfall recovery in West Africa. *International Journal of Climatology*, *35*(15), 4589–4605.

Sarr, M. A., Zoromé, M., Seidou, O., Bryant, C. R., & Gachon, P. (2013, November). Recent trends in selected extreme precipitation indices in Senegal – A changepoint approach. *Journal of Hydrology*, *505*, 326–334.

Scheff, J., & Frierson, D. M. W. (2015, July). Terrestrial Aridity and Its Response to Greenhouse Warming across CMIP5 Climate Models. *Journal of Climate*, *28*(14), 5583–5600.

Schneider, T., Bischoff, T., & Haug, G. H. (2014, September). Migrations and dynamics of the intertropical convergence zone. *Nature*, *513*(7516), 45–53.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., . . . Teuling, A. J. (2010, May). Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews*, *99*(3-4), 125–161.

Seth, A., Rauscher, S. A., Biasutti, M., Giannini, A., Camargo, S. J., & Rojas, M. (2013, October). CMIP5 Projected Changes in the Annual Cycle of Precipitation in Monsoon Regions. *Journal of Climate*, *26*(19), 7328–7351.

Shekhar, R., & Boos, W. R. (2017). Weakening and Shifting of the Saharan Shallow Meridional Circulation During Wet Years of the West African Monsoon . *Journal of Climate*.

Sillmann, J., Kharin, V., Zwiers, F., Zhang, X., & Bronaugh, D. (2013, March). Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections.

Journal of Geophysical Research-Atmospheres, *118*(6), 2473–2493.

Stith, M., del Corral, J., Adamo, S., de Sherbinin, A., Stith, M., Giannini, A., … de Sherbinin, A. (2016, February). A Quantitative Evaluation of the Multiple Narratives of the Recent Sahelian Regreening*. *dx.doi.org*, *8*(1), 67–83.

Stratton, R. A., Senior, C. A., Folwell, S. S., Earnshaw, P. D., Lock, A. P., Manners, J., … Wilkinson, J. M. (2018, April). A Pan-African Convection-Permitting Regional Climate Simulation with the Met Office Unified Model: CP4-Africa. *Journal of Climate*, *31*(9), 3485–3508.

Sultan, B., Guan, K., Kouressy, M., Biasutti, M., Piani, C., Hammer, G. L., … Lobell, D. B. (2014, October). Robust features of future climate change impacts on sorghum yields in West Africa. *Environmental Research Letters*, *9*(10), 104006.

Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M., … Baron, C. (2013, March). Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. *Environmental Research Letters*, *8*(1), 014040.

Tambo, J. A., & Abdoulaye, T. (2012, September). Smallholder farmers' perceptions of and adaptations to climate change in the Nigerian savanna. *Regional Environmental Change*, *13*(2), 375–388.

Taylor, C. M., Belušić, D., Guichard, F., Parker, D. J., Vischel, T., Bock, O., … Panthou, G. (2017, April). Frequency of extreme Sahelian storms tripled since 1982 in satellite observations. *Nature*, *544*(7651), 475–478.

Taylor, C. M., de Jeu, R. A. M., Guichard, F., Harris, P. P., & Dorigo, W. A. (2012, September). Afternoon rain more likely over drier soils. *Nature Geoscience*, *489*(7416), 423–426.

Taylor, C. M., Gounou, A., Guichard, F., Harris, P. P., Ellis, R. J., Couvreux, F., & De Kauwe, M. (2011). Frequency of Sahelian storm initiation enhanced over mesoscale soil-moisture patterns. *Nature Geoscience*, *4*(7), 430–433.

Taylor, C. M., & Lebel, T. (1998, June). Observational Evidence of Persistent Convective-Scale Rainfall Patterns. *Monthly Weather Review*, *126*(6), 1597–1607.

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012, April). An Overview of CMIP5 and the

Experiment Design. *Bulletin of the American Meteorological Society*, *93*(4), 485–498.

Timm, O., Köhler, P., Timmermann, A., & Menviel, L. (2010, May). Mechanisms for the Onset of the African Humid Period and Sahara Greening 14.5–11 ka BP*. *Journal of Climate*, *23*(10), 2612–2633.

Uddling, J., Broberg, M. C., Feng, Z., & Pleijel, H. (2018, June). Crop quality under rising atmospheric CO2. *Current Opinion in Plant Biology*.

Usman, M., Nichol, J. E., Ibrahim, A. T., & Buba, L. F. (2018, October). A spatio-temporal analysis of trends in rainfall from long term satellite rainfall products in the Sudano Sahelian zone of Nigeria. *Agricultural and Forest Meteorology*, *260-261*, 273–286.

Vizy, E. K., & Cook, K. H. (2017, May). Seasonality of the Observed Amplified Sahara Warming Trend and Implications for Sahel Rainfall. *Journal of Climate*, *30*(9), 3073–3094.

Wang, B., & Ding, Q. (2008, March). Global monsoon: Dominant mode of annual variation in the tropics. *Dynamics of Atmospheres and Oceans*, *44*(3-4), 165–183.

West, C. T., Roncoli, C., & Ouattara, F. (2008). Local perceptions and regional climate trends on the Central Plateau of Burkina Faso. *Land Degradation & Development*, *19*(3), 289–304.

Wieder, W. R., Cleveland, C. C., Smith, W. K., & Todd-Brown, K. (2015, June). Future productivity and carbon storage limited by terrestrial nutrient availability. *Nature Geoscience*, *8*(6), 441–444.

Wu, M.-L. C., Reale, O., Schubert, S. D., Suarez, M. J., Koster, R. D., & Pegion, P. J. (2009, September). African Easterly Jet: Structure and Maintenance. *Journal of Climate*, *22*(17), 4459–4480.

Xie, S.-P., Deser, C., Vecchi, G. A., Collins, M., Delworth, T. L., Hall, A., ... Watanabe, M. (2015, September). Towards predictive understanding of regional climate change. *Nature Climate Change*, *5*(10), 921–930.

Xue, Y., Boone, A., & Taylor, C. M. (2012). Review of Recent Developments and the Future Prospective in West African Atmosphere/Land Interaction Studies. *International Journal of Geophysics*, *2012*(14), 1–12.

Yoshioka, M., Mahowald, N. M., Conley, A. J., Collins, W. D., Fillmore, D. W., Zender, C. S.,

& Coleman, D. B. (2007, April). Impact of Desert Dust Radiative Forcing on Sahel Precipitation: Relative Importance of Dust Compared to Sea Surface Temperature Variations, Vegetation Changes, and Greenhouse Gas Warming. *Journal of Climate*, *20*(8), 1445–1467.

Zappa, G., & Shepherd, T. G. (2017, August). Storylines of Atmospheric Circulation Change for European Regional Climate Impact Assessment. *Journal of Climate*, *30*(16), 6561–6577.

Zeng, N., Neelin, J., Lau, K., & Tucker, C. (1999). Enhancement of interdecadal climate variability in the Sahel by vegetation interaction. *Science*, *286*, 1537–1540.

Zhai, J., & Boos, W. R. (2017, September). The drying tendency of shallow meridional circulations in monsoons. *Quarterly Journal of the Royal Meteorological Society*, *143*(708), 2655–2664.

Zhang, R., & Delworth, T. (2005). Simulated Tropical Response to a Substantial Weakening of the Atlantic Thermohaline Circulation. *Journal of Climate*, *18*(12), 1853–1860.

Zhang, R., Delworth, T. L., Sutton, R. T., Hodson, D. L. R., Dixon, K. W., Held, I. M., … Vecchi, G. A. (2013, April). Have Aerosols Caused the Observed Atlantic Multidecadal Variability? *J. Atmos. Sci.*, *70*(4), 1135–1144.

Zhang, W., Brandt, M., Guichard, F., Tian, Q., & Fensholt, R. (2017, July). Using long-term daily satellite based rainfall data (1983–2015) to analyze spatio-temporal changes in the sahelian rainfall regime. *Journal of Hydrology*, *550*, 427–440.