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Impact of Land–Atmosphere Interactions on Sahel Climate

Yongkang Xue

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Summary and Keywords

The Sahel of Africa has been identified as having the strongest land–atmosphere (L/A) interactions on Earth. The Sahelian L/A interaction studies started in the late 1970s. However, due to controversies surrounding the early studies, in which only a single land parameter was considered in L/A interactions, the credibility of land-surface effects on the Sahel's climate has long been challenged. Using general circulation models and regional climate models coupled with biogeophysical and dynamic vegetation models as well as applying analyses of satellite-derived data, field measurements, and assimilation data, the effects of land-surface processes on West African monsoon variability, which dominates the Sahel climate system at intraseasonal, seasonal, interannual, and decadal scales, as well as mesoscale, have been extensively investigated to realistically explore the Sahel L/A interaction: its effects and the mechanisms involved.

The Sahel suffered the longest and most severe drought on the planet in the 20th century. The devastating environmental and socioeconomic consequences resulting from drought-induced famines in the Sahel have provided strong motivation for the scientific community and society to understand the causes of the drought and its impact. It was controversial and under debate whether the drought was a natural process, mainly induced by sea-surface temperature variability, or was affected by anthropogenic activities. Diagnostic and modeling studies of the sea-surface temperature have consistently demonstrated it exerts great influence on the Sahel climate system, but sea-surface temperature is unable to explain the full scope of the Sahel climate variability and the later 20th century's drought. The effect of land-surface processes, especially land-cover and land-use change, on the drought have also been extensively investigated. The results with more realistic land-surface models suggest land processes are a first-order contributor to the Sahel climate and to its drought during the later 1960s to the 1980s, comparable to sea surface temperature effects. The issues that caused controversies in the early studies have been properly addressed in the studies with state-of-the-art models and available data.

The mechanisms through which land processes affect the atmosphere are also elucidated in a number of studies. Land-surface processes not only affect vertical transfer of radiative fluxes and heat fluxes but also affect horizontal advections through their effect on the atmospheric heating rate and moisture flux convergence/divergence as well as horizontal temperature gradients.

Keywords: Sahel, land–atmosphere interactions, land use, land cover, desertification, West African monsoon, drought, West African Monsoon Modeling and Evaluation (WAMME), African Monsoon Multidisciplinary Analysis (AMMA)

The importance of land-surface processes in the climate system has been extensively investigated. A number of regions in the world, such as the Sahel (Koster et al., 2004; Xue et al., 2004A), Amazon (Nobre et al., 2004), and Asian monsoon regions (Fu et al., 2004; Xue et al., 2004B), have been identified as hot spots of land–atmosphere (L/A) interactions, where interactions through feedback loops play a crucial role in the surface water and energy balances as well as regional climate. In a global and seasonal study, which assessed regions of the Earth with strong L/A interactions, the Sahel has been identified as a region with the strongest L/A interactions on Earth (Xue et al., 2010B). In addition, significant L/A interactions in central and eastern Africa and southern Africa have been identified (Xue et al., 2010B); however, they have not been comprehensively investigated so far. Sahel L/A interactions, which have been comprehensively investigated in numerous studies for four decades, are the focus here.

Historical Background of Sahelian Land and Climate Conditions

The Sahel is a tropical, semi-arid region (approximately 3 million km^2) along the southern perimeter of the Sahara Desert and covers large parts of six African countries and smaller parts of six more. It stretches from the Atlantic Ocean eastward to the Red Sea. The word “Sahel” is derived from the Arabic for “shore” or “coast,” and this was seemingly how the vegetation cover appeared to early traders who entered the region from the Sahara Desert.

The region has experienced dramatic episodes of land-cover changes in history (see Alexandre et al., 1997; Saltzmann and Martyn, 1998; Claussen and Gayler, 1997; Waller et al., 2007). The Sahara Desert covered a very large area extending to the early 21st century’s Sahelian region around ca. 16,000 before present (BP), when the climate was extremely cold and dry, corresponding to the maximum glacial period. From 10,000 to ca. 5,000 years BP, in the early and mid-Holocene, when the climate became considerably more humid than today, swamp forest vegetation was established in the interdune depression in the Nigerian Sahel. The vegetation limit in the region reached at least 23ºN. However, during the driest phase in the late Holocene (ca. 4000 and 1200 BP), starting with the thinning of the dense forest, the land cover was gradually replaced by a short-grass savanna. The modern shrubs and savanna developed ca. 700 BP, with the wetter climate condition that started from ca. 1000 BP.

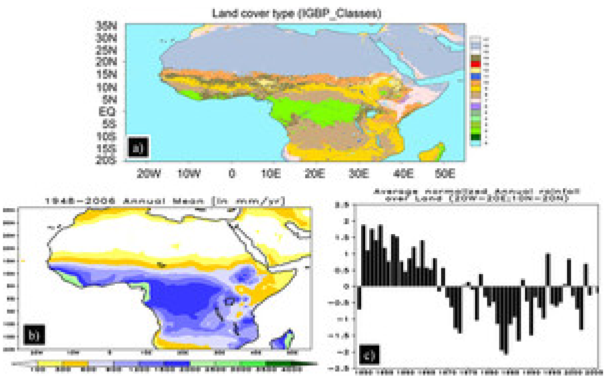

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Figure 1. (a) Land-cover classification map based on MODIS satellite products. Type 2, evergreen broadleaf; type 4, deciduous broadleaf; type 6, closed shrubland; type 7, open shrublands; type 8, woody savannas; type 9, savannas; type 10, grasslands; type 12, croplands; type 16, barren or sparsely vegetated. Only relevant types in this map are listed. (b) Observed climatological annual mean precipitation (mm yr^{-1}) based on Climate Research Unit data (New et al., 1999). (c) Time series of annual

precipitation anomaly (mm day^{-1}) averaged over 20ºW to 20ºE and 5ºN to 20ºN.

In the 20th century, the Sahel is a bioclimatic zone of predominantly annual grasses, shrubs, crops, and trees (Figure 1A). There is a steep gradient in climate, soils, vegetation, and land use, from the almost lifeless Sahara Desert in the north to savannas in the south. The similarity of climate and land cover in the East–West direction contrasts dramatically with the strong North–South gradient (Figure 1B). The uniformity of this geographical pattern is partly a result of lack of rapid changes in topography, but also because of the zonal nature of the climate, with desert to the north and ocean or tropical forests to the south. The geographical patterns of rainfall, vegetation cover, soils, and land use all share this zonal arrangement and are strongly correlated with each other, so that cause and effect among these processes are hard to disentangle.

The Sahel has experienced significant climate anomalies and suffered the most severe and longest drought in the world during the 20th century. The climate variability shows one of the strongest interdecadal signals on the planet in the 20th century (Redelsperger et al., 2007). Annual rainfall has persistently remained below the long-time average since the late 1960s, with devastating droughts hitting during the late 1960s and the early 1980s. Starting from the late 1980s, however, there has been evidence of some rainfall recovery relative to the very dry period (Figure 1C; Hulme, 1994; Lebel & Ali, 2009; Nicholson et al., 2012). The severe droughts and drought-induced famines have had devastating environmental and socioeconomic consequences, which have provided strong motivation for the scientific community and society to understand West African climate variability and causes of the Sahel drought. The West African climate is strongly affected by external forces. Among them, the sea-surface temperature (SST), land-surface processes, and aerosols have been considered major factors (see Lau et al., 2006; Rodriguez-Fonseca et al., 2015; Xue et al., 2004A, 2012). In this article, the Sahel L/A interaction is the main focus.

Development of Early Sahelian L/A Interaction Studies and the Controversies

The Sahelian continental-scale land mass and relatively flat orography (excluding the eastern Sahel) warrant that L/A interactions play a major role in the regional climate and also make such interactions relatively easily detected in model simulations (Xue et al., 2004A). Model studies of Sahel L/A interactions started in the later 1970s and were largely motivated by the Sahel drought during the late 1960s to the 1980s. Due to simple land-surface parameterization schemes at that time, the land-surface properties that regulate the L/A interactions were regarded as separable parameters that could be independently prescribed as boundary conditions in climate models. In most early modeling studies, only a single land-surface parameter was tested each time. The primary land parameters under investigation were surface albedo, soil moisture, and combinations of the two, as well as surface roughness length (see Charney, 1975; Charney et al., 1977; Kitoh et al., 1988; Laval and Picon, 1986; Sud and Fennessy, 1982; Sud et al., 1988; Walker and Rowntree, 1977).

The modeling studies often explicitly or implicitly were intended to investigate how land degradation affected the 1970s Sahel droughts, and they normally consisted of two cases, one with low albedo and/or high soil moisture, and another with high surface albedo and/or low soil moisture, which mimicked the desertification conditions. In the albedo study, when the surface albedo became high, more shortwave radiation reflected back to the atmosphere from land surface and was lost to space. Surface and atmosphere became cool, inducing a relative sinking motion, which would suppress precipitation (Figure 2). In the soil moisture study, the lower soil moisture and associated less surface evaporation would reduce atmospheric humidity and cloud cover, then precipitation. The modeling studies consistently demonstrated that the land surface had substantial impact on the Sahel climate, which greatly stimulated public interest and spurred more scientific research on this subject during the later 1970s and the early 1980s.

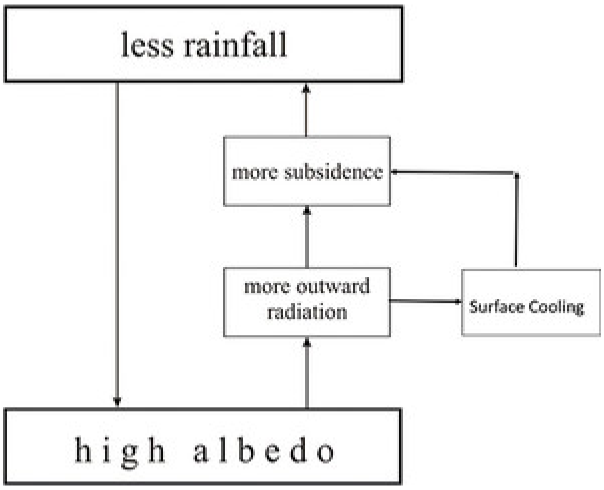

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Figure 2. Schematic diagram of albedo feedback processes.

However, in most of the sensitivity studies, the extent of areas associated with changes in land-surface conditions, such as albedo and soil moisture, were somewhat arbitrary (Los et al., 2006). To obtain large impacts from the land parameter changes, the changes in the magnitudes of the parameters were usually unrealistically large. For instance, in the early albedo study (Charney et al., 1977), albedo was changed from 0.14 to 0.35 in the land-degradation case. Based on satellite observations, it has been found that only a change of less than 0.1 in surface albedo in the Sahel over different time periods might be a reasonable estimate (Courel et al., 1984; Govaerts & Lattanzio, 2008; Nicholson et al., 1998; Norton et al., 1979), much less than what was specified in Charney et al.'s study (1977). Moreover, the cooling caused by changes in high surface albedo alone are not supported by observations over land-degraded areas. Furthermore, Rodwell and Hoskins (1996) pointed out that the time-mean horizontal-advection in the West African monsoon (WAM) area was perhaps twice as strong as the time-mean diabatic-cooling term caused by the albedo change. Without sufficient circulation change induced by the surface process, as done in the early albedo study, the specified changes in surface parameters, such as albedo, had to be unrealistically large to produce substantial atmospheric response. As a result of these critical issues in question, the credibility of the land-degradation effect on the Sahel drought has long been challenged (see Los et al., 2006; Ripley, 1976).

Sahelian L/A Interactions at Large Scales

Land-surface/atmosphere interactions are very complex in the real world and involve many processes and associated parameters. The land effect on the regional climate can be realistically assessed only when all dominant processes that control major comparable components of the surface water and energy balances are considered. To adequately assess the impact of land processes, especially land degradation, on the Sahelian climate variability and drought, more sophisticated soil-vegetation-atmosphere transfer models (SVATs) have been introduced to Sahel study (see Xue et al., 1990). In contrast to studies in the early 1980s, some of the newer studies not only tested the sensitivity of the regional climate to land-surface processes but also intended to link the land-surface processes to observed seasonal to decadal climate anomalies and to investigate predictability and prediction with more realistic land processes, i.e., whether introducing adequate land-surface processes improves the simulation of the WAM, enhances predictability at different scales, and more realistically explores the possible mechanisms involved. The Sahel climate is dominated by the WAM system. Monsoon circulations are forced and maintained by sea-land thermal contrasts and by surface heat released into the atmosphere. Therefore, the WAM/land interaction was a major issue in these studies.

Assessment of Effects of Land-Surface Processes in the Sahel Climate System at Different Scales (Modeling Studies)

Modeling studies and satellite-derived products have been applied to assess the importance of the land surface in the climate system. Xue et al. (2004B, 2010B) conducted numerical experiments using general circulation models (GCMs) coupled to different parameterizations with varying degrees of physically based complexity in the representation of land-surface processes. Since a more realistic representation of biophysical processes in a GCM should improve precipitation simulations if land-surface processes indeed have effects on the real climate system, statistically significant improvement in precipitation simulation with more realistic biophysical representation at the surface in models has been adopted as a criterion to identify land effects. Figure 3 shows the reduced absolute seasonal mean bias of climatological precipitation simulations, which represents improved prediction skill, due to more realistic biophysical process in the GCM. The results suggest that biophysical processes have a strong effect in the monsoon regions; among them, West Africa shows the largest impact in the world, especially during the summer and the fall, with some impact during spring. The biophysical process' importance for the WAM has also been demonstrated by the application of satellite-derived vegetation products, such as leaf area index (LAI), and vegetation coverage in the GCM. By using remotely sensed LAI datasets, instead of using LAI based on a few ground surveys, the GCM produced substantial improvements in the near-surface climate in the WAM regions (Kang et al., 2007). In another multimodel study assessing soil moisture/atmosphere coupling strength (Koster et al., 2004), the importance of Sahel soil moisture has been identified, which reveals that the Sahel, along with a few other regions, has the greatest soil moisture/climate coupling strength in the world.

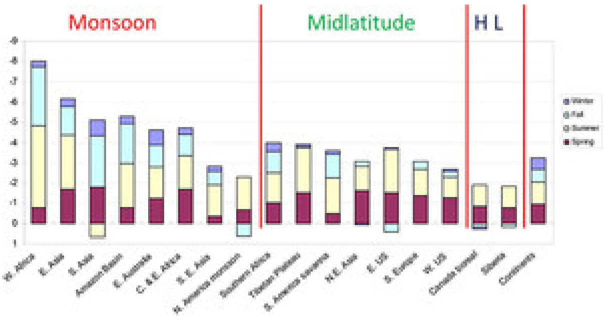

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Figure 3. Reduced absolute seasonal mean bias of climatological precipitation (mm day^{-1}) simulations, which represent improved prediction skill, due to more realistic biophysical processes in contrast to no biophysical processes in GCM surface parameterizations.

(Adapted from Xue et al., 2010B.)

However, there were also studies challenging the role of soil moisture in the Sahel study. Some modeling studies (Douville et al., 2007; Shinoda & Yamaguchi, 2003) have showed that the root-zone soil moisture did not act as a memory of rainfall anomaly that would produce an effect in the following rainy season, and therefore, it is not found to be related to the long-term persistence of the drought. Koster et al. (2004) also showed that although the average over 12 participating models' simulations indicated the Sahel area had higher coupling strength, substantial discrepancies existed among the models.

Along with the seasonal mean, the land processes also show effects on the intraseasonal climate variability at large scales. The studies showed that vegetation properties played a significant role in the intraseasonal variations of precipitation and circulation over West Africa (Xue et al., 2004A), and intraseasonal soil moisture fluctuations were intense enough to feed back on the low-level vorticity structure (Taylor, 2008). In another study with a regional model, it has been shown that, with a more realistic biophysical representation at the surface, the seasonal timing and magnitude of mean monsoon precipitation more closely match observations, especially the timing of the monsoon advance and retreat across the Guinean Coast (Steiner et al., 2009).

In the studies described so far, surface vegetation conditions were specified without interannual variability and did not respond to climate variability. In the real world, vegetation also responds to climate variability and change. Using a biophysical/dynamic vegetation model driven by observed climate forcing, it has been found that vegetation LAI over the Sahel showed a decreasing trend from the 1950s to the 1980s and a partial recovery after the 1980s (Xue et al., 2016A; Figure 4A), which should also affect the regional climate. To include considerations of two-way L/A interaction, dynamic vegetation models have been introduced to atmospheric models. Some studies have been employed to investigate the climate equilibrium states. For example, using a GCM with an interactive vegetation model, Claussen and Gayler (1997) found multiple equilibrium states in climate/vegetation dynamics in northern Africa, which could not be found in other parts of the world. This discovery was confirmed by Wang and Eltahir (2000) with a coupled two-dimensional climate/dynamic vegetation model. In another study using a coupled atmosphere and dynamic vegetation model, Zeng et al. (1999) produced the decadal precipitation variability in the Sahel, which could not be simulated if interactive vegetation processes were not included in their model.

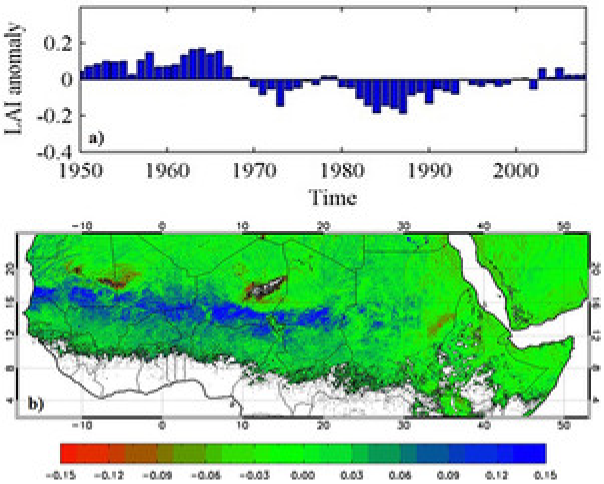

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Figure 4. (a) A dynamic vegetation model-simulated temporal evolution of LAI anomaly over Sahel. (b) Mean August-September-October surface albedo difference between 1984 and 2003 over the Sahel region. Missing data are shown in white.

Adapted from Xue et al. (2012), which is based on Govaerts and Lattanzio (2008).

In addition to the land-surface process' role in modern Sahel climate, the L/A interaction has also been suggested to have played a role in the Sahelian Paleo climate (Braconnot et al., 2000; Claussen et al., 1999; Kutzbach et al., 1996). The subtle changes in Earth's orbit, strongly amplified by climate-vegetation interactions, are currently believed to be the main causes for the wetter conditions in the region's climate 9,000 to 6,000 years ago. Numerical simulations with climate models have shown that, although changes in Earth's orbital parameters (eccentricity of the Earth's orbit, axial tilt of Earth, and the date of perihelion) increased the amplitude of the seasonal cycle of solar radiation in the Northern Hemisphere and strengthened the WAM, only after including the consideration of L/A interactions was the model able to simulate a much wetter Sahel. The WAM precipitation from this simulation was able to drive a biome model to produce the Sahara/Sahel boundary, which is close to Paleo vegetation observations (Kutzbach et al., 1996). In another Paleoclimate Modeling Intercomparison Project (PMIP) study, it was found that during the Last Glacial Maximum and the Mid-Holocene the position of the maximum of surface temperature controlled the position of the intertropical convergence zone (ITCZ) simulated by all the models (Braconnot et al., 2000).

Assessment of Effects of Land-Surface Processes in the Sahel Climate System at Different Scales (Data Analyses Studies)

After satellite data began to be available from the late 1970s, a large number of analyses based on satellite-derived vegetation products have been carried out. Despite limitations in the studies due to data quality questions caused by measurement and data processing errors, robustness in statistical methods applied, and uncertainty about using satellite products to represent real vegetation conditions, the results nevertheless provide another path to assess the vegetation/atmosphere interactions and offer a new and valuable reference to compare with model-simulated vegetation/atmosphere interactions.

Among the products, the normalized difference vegetation index (NDVI), the fraction of photosynthetically active radiation (FPAR), albedo, and LAI have been used the most. For example, the decadal trends of the satellite-derived products were the subject of some diagnostic studies. Studies have found an increase in NDVI/LAI and a decrease in surface albedo over the Sahel during the period 1982–1999 (Eklundh & Olsson, 2003; Govaerts & Lattanzio, 2008; Hiernaux et al., 2009, Figure 4B), which are interpreted as a vegetation recovery from the very dry periods of the 1980s. Moreover, annual NDVI was found to be highly correlated to annual precipitation of the concurrent year and the previous year in the southern Sahel (Martiny et al., 2005). Using a statistical model of vegetation greenness and NDVI, Los et al. (2006) also suggested the previous year's vegetation growth affects greenness in the following year. The statistical model found that these vegetation-rainfall interactions increased the interannual variation in Sahelian precipitation, accounting for as much as 30% of the variability in annual precipitation in some sub-Sahel regions between 15º and 20ºN. In a seasonal study, Liu et al. (2006) found that the FPAR-led correlations with precipitation in the Sahel are positive in spring and summer but become negative in fall and winter. However, in another study using NDVI from 1982 to 2006 (He & Lee, 2016), the spring and summer NDVIs over the Sahel have significant negative and positive correlations, respectively, with summer Sahel rainfall. A Granger causality test found that only summer NDVI over the Sahel causes summer rainfall over the Sahel. Although analyses of these satellite products and climate data have confirmed a close relationship between vegetation conditions and precipitation at different scales and generally support the results from modeling studies for the role of vegetation effects during the summer WAM, there are discrepancies among the analyses and between the model results and satellite data analyses in other seasons. Further studies with more data are imperative.

In addition to the satellite data, data from large-scale field campaigns are also available from the African Monsoon Multidisciplinary Analysis (AMMA) project (Lebel et al., 2011). Distinct from the previous Sahel observational efforts (e.g., Prince et al., 1995) which encompassed only one or a few sites, the AMMA program's activities in data collection aimed to increase the understanding and improve the modeling of the WAM/land interactions over a wide range of spatial and time scales (Redelsperger et al., 2007). The AMMA Land Surface Model (LSM) Intercomparison Project (ALMIP; Boone et al., 2009; Figure 5) employed these AMMA observational data plus other best available data to drive multi state-of-the-art offline land models to produce a best set of land flux estimations over West Africa for large-scale A/L interaction studies. The ALMIP LSM outputs for the period 2002–2007 have been compared with satellite-derived surface brightness temperature (de Rosnay et al., 2009), satellite-based soil water-storage estimates (Grippa et al., 2011), and many others. ALMIP provides a robust regional-scale estimate of land-surface state variables and fluxes from an ensemble of state-of-the art land-surface models. Because the ALMIP data cover most of West Africa, this dataset can be considered as one of the best currently available proxies for large-scale estimates of the land-surface state over West Africa for different applications.

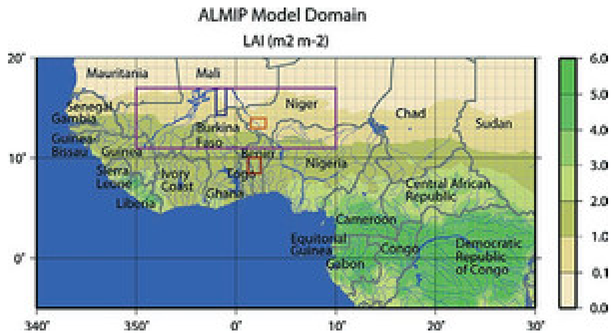

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Figure 5. The ALMIP regional-scale model domain. The three mesoscale supersites are indicated by boxes: Mali (blue), Niger (orange), and Benin (red). The Sahel box is represented also (violet). The color shading corresponds to the annual average leaf area index (LAI; $m^2\ m^{-2}$) from the Ecoclimap database.

(Adapted from Bonne et al., 2009.)

The ALMIP products have been applied to the West African Monsoon Modeling and Evaluation (WAMME) project (Xue et al., 2010A) for large-scale African L/A interaction studies (Boone et al., 2010). The WAMME is the first international model intercomparison project specifically designed to evaluate current state-of-the-art GCMs and regional climate models (RCMs) for simulating WAM precipitation, especially drought scenarios and their relevant processes (Druyan et al., 2010; Xue et al., 2010A). It has been found that, although simulated net radiation within WAMME GCMs and RCMs generally agrees rather well with ALMIP, the partitioning of this energy into latent heat and sensible heat fluxes from different GCMs is different from ALMIP and is quite variable. Furthermore, ALMIP produces the maximum latent heat flux during the period of monsoon retreat as stored water is evaporated before solar radiation reaches the boreal winter minima; although the GCM and RCM ensemble means produced this feature, many models failed to simulate this seasonal variability. Finally, in contrast to ALMIP results and local-scale observations that indicate values on average of the meridional ratio of sensible heat flux to net radiation to be approximately 0.35, the ratio becomes quite low (generally less than 0.10) from the Sahel to the southern coast of West Africa during the core monsoon season for nearly all of the WAMME models. These evaluations identify weaknesses in current West African climate modeling and should contribute to further model development for Sahel L/A interaction studies.

Sahelian Land-Use Land-Cover Change (LULCC) Studies and Sahel Drought During the Late 1960s to 1980s

The Sahel L/A interaction studies were rooted in the desire to explore the relationship between the late 1960s to 1980s Sahel drought and the LULCC there. The Sahelian area has experienced substantial land degradation (see D'Odorico et al., 2013; Xue et al., 2004A; Figure 6). With more realistic land biophysical processes in climate models and evidence of LULCC over the region, this effect has been comprehensively evaluated. In the experiments (Boone et al., 2016; Xue, 1997; Xue & Shukla, 1993), the GCM was integrated using a "normal" vegetation map (control simulation) and a vegetation map where savanna or shrubs with ground cover were replaced by shrubs with bare soil in a specified area over Sahel, representing land degradation there in the 1980s (degraded simulation). Different vegetation and soil properties, including surface albedo, LAI, soil hydraulic conductivity, and surface roughness length, which are associated with the vegetation and soil types, were also changed according to the vegetation maps. Since there was no quantitative data available for 1950s land-cover information in the Sahel, the selections of the degradation areas were based on then-available information (e.g., Dregne & Chou, 1992), but it did not necessarily represent the reality that occurred from the 1950s to the 1980s. As a result, the simulations must be regarded as sensitivity studies. Because of the internal variability in GCMs, ensemble means were used to identify climate impacts.

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Figure 6. The photos show the common practices of burning and slash agriculture and fuel wood collection in Mali in 2005.

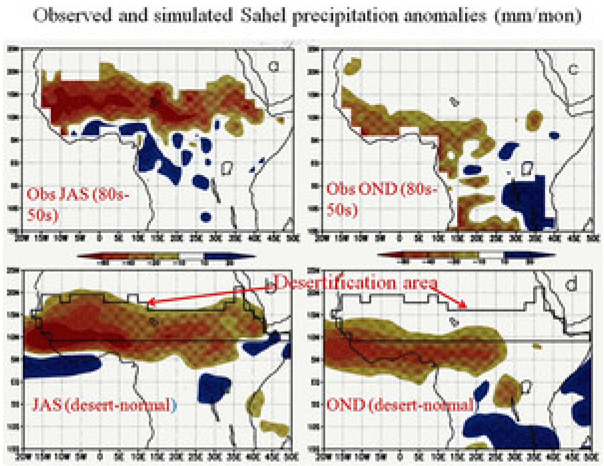

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Figure 7. (a) Observed JAS rainfall difference (mm month^{-1}) between 1980s and 1950s. (b) JAS rainfall difference in ensemble mean, degraded experiment minus control experiment. (c) Same as (a) but for OND. (d) Same as (b) but for OND. In the degraded simulations, the vegetation types in the heavy lines were changed to shrubs with bare soil.

(Adapted from Xue, 1997.).

During the 1980s Sahel drought, rainfall was reduced in the Sahel but increased slightly to the south (Figure 7A), showing a shift in the intertropical convergence zone (ITCZ; Xue & Shukla, 1993). Differences between the ensemble mean July-August-September (JAS) rainfall of the degraded and control simulations are shown in Figure 7B (Xue et al., 2004A). The rainfall changes are statistically significant at the *t*-test α = 0.01 level in areas with precipitation difference larger than 15 mm mon^{-1} (Figures 7B and 7D). The simulated rainfall in the degraded area (from 9ºN to 17ºN, and 15ºW to 43ºE) is reduced by 1.3 mm day^{-1}, close to the 1.5 mm day^{-1} observed reduction (about 87% of the precipitation in the control run). During the beginning of the Sahelian dry season (October-November-December, OND), when ITCZ moves back to the south, the areas of reduced rainfall related to land degradation also shift to the south of the Sahel, with a positive anomaly over eastern Africa (Figure 7D), consistent with the observed OND rainfall anomaly (Figure 7C). The JAS surface air temperature is higher in the degraded simulation than the control due to substantially reduced evapotranspiration, consistent with the observed JAS temperature difference between the 1980s and the 1950s (Xue, 1997). In the degraded area, the simulated surface air temperature increases by 0.8 ºC, close to the observed increase over the same area, 1 ºC.

Since there is uncertainty about the exact extent of land degradation from the 1950s to the 1980s, in another set of tests that was designed to investigate how the locations and extent of specified land-surface changes may affect the results, five subregions were degraded in turn: northern Sahel, southern Sahel, West Africa, East Africa, and the coast area along the Gulf of Guinea (Clark et al., 2001). Although degradation always results in reduced rainfall over the changed surface, degradation in the northern Sahel and West African Sahel result in the largest and most significant reductions of rainfall. In particular, degradation of the northern Sahel causes widespread reduction of rainfall across tropical North Africa, both within and outside the degraded area.

The impact of large-scale afforestation in the sub-Sahara on the regional climate has also been investigated (Xue & Shukla, 1996). The results suggest that afforestation would enhance the rainfall in the region and would have the largest impact during dry years. While rainfall increased in the afforestation area, it decreased to the south of that region. It was found that this land-surface change altered the surface energy balance and induced the surface-temperature gradient and circulation change that led to a change in rainfall. The comparisons with desertification studies show a number of important differences and suggest that the response to changes in land-surface properties is not linear and that the climate in the Sahel is especially vulnerable to the nature and location of the land-surface perturbation, because the Sahel region is near the edge of the subsidence branch of the Hadley circulation. The geographic locations of the afforestation area and species selected affected its influence.

Biomass burning is a widespread phenomenon in the Sahel during the dry season. An RCM study investigated the impact of vegetation condition and surface albedo change over the satellite-observed burned areas on the surface energy balance and WAM monthly precipitation in northern Africa (De Sales et al., 2016). It was found that land condition over the burned area resulted in a decrease in precipitation over sub-Saharan Africa, associated with the weakening of the West African monsoon progression through the region. A decrease in atmospheric moisture flux convergence in the burned area played a dominant role in reducing precipitation in the area, especially in the months preceding the monsoon onset. The areas with the largest precipitation impact were those covered by savannah and rainforest.

Large-scale irrigation is another important practice in the Sahel, and it substantially modifies the soil moisture. In an RCM study over an area in East African Sahel (Alter et al., 2015), it was found that, after imposition of the irrigation scheme, the irrigation inhibits rainfall over the irrigated area and enhances rainfall to the east. Observational analyses of rainfall, temperature, and streamflow in the same region indicate that, with irrigation, the RCM produces more realistic results. This study suggests irrigation development can consistently modify rainfall patterns in and around irrigated areas, warranting further examination of potential agricultural, hydrologic, and economic implications.

SST anomalies have long been considered to be the main (or even the only) cause of the 1980s Sahel drought. At interannual time scales, the warming of the equatorial Atlantic, Pacific, and Indian Oceans results in rainfall reduction over the Sahel; the warming SST anomalies over the Mediterranean Sea, however, seem to relate to increased rainfall (see Biasutti et al., 2008; Folland et al., 1986; Giannini et al., 2003; Hastenrath & Lamb, 1977; Janicot et al., 1996; Rowell, 2003; Vizy & Cook, 2002). At decadal time scales, the Sahel drought has been associated with the effects of an interhemispheric dipole pattern of SST anomalies that is global, but most pronounced in the Atlantic basin (Folland et al., 1986). The differential heating of the Northern and Southern Hemisphere leads to a meridional shift of the ITCZ. The anomalous SST patterns have been linked to the positive phase of the interdecadal and decadal Pacific oscillation (Mantua et al. 1997; Mohino et al., 2011;

Zhang et al. 1997), and the negative phase of the Atlantic multidecadal oscillation (AMO; Knight et al., 2005). A comprehensive review of SST effects has been presented in Rodriguez-Fonseca et al. (2015). However, in the past, this effect and land effects were evaluated separately for several decades. To assess and compare the relative effect of LULCC and SST on the Sahel drought, and therefore the role of natural variability and anthropogenic activity in the Sahel drought, the WAMME project (Xue et al., 2010A, 2016A) was carried out to evaluate the ability of current state-of-the-art GCMs and RCMs to simulate WAM precipitation, especially the 1980s drought, and its related processes, and to improve understanding of the possible roles and feedbacks of SST, LULCC, and aerosol forcings in the Sahel climate system at seasonal to decadal scales. The project's strategy is to apply prescribed observationally based anomaly forcing, i.e., "idealized but realistic" forcing, in simulations by climate models. The goal is to assess the forcings' effects in producing/amplifying seasonal and decadal climate variability in the Sahel between the 1950s and the 1980s. This is the first multimodel experiment specifically designed to simultaneously evaluate such relative contributions from different forcings to the 1980s Sahel drought.

A recently available land-use map was employed (Hurtt et al., 2006) in the second WAMME experiment (WAMME II). This map, which combines crop and pasture area change in past centuries over West Africa, was derived from global land-use history products (Goldewijk, 2001; Ramankutty & Foley, 1999) and was employed for Phase 6 of the Coupled Model Intercomparison Project (CMIP6) LULCC experiment (Hurtt et al., 2011). Since there is still no detailed information on the changes of vegetation variables from the 1950s to the 1980s, heterogeneity in land degradation (Xue et al., 2004A) is ignored, and the magnitude of the land perturbation in the experiments may be overestimated. However, because land degradation due to natural vegetation variability caused by the dry trend from the 1950s to the 1980s (Figure 4A; Xue et al., 2016A) was not included and a study has shown that two-way vegetation-climate interactions would enhance the severity of drought (Wang et al., 2004), the imposed land forcing in the WAMME II should provide a reasonable assessment of land effects in the 1980s drought.

Under the influence of the maximum possible SST forcing and LULCC forcing in the WAMME II experiment, the ensemble mean of WAMME II models can produce up to 60% and 40% of the precipitation difference between the 1980s and the 1950s, respectively. The WAMME II results also identify the role of SSTs in triggering and maintaining the Sahel drought and the role of land-surface processes in responding to and amplifying the drought (Xue et al., 2016A). With better land-degradation data, better experimental design, and multimodel efforts, the WAMME experiments provide more realistic assessment of the land effect than the early sensitivity studies, which produced 86% rainfall reduction (Xue, 1997). The WAMME suggests that land-surface processes are a first-order contributor to the Sahel drought of the 1980s and to the West African climate system in general. The results also suggest that catastrophic consequences are likely to occur in the regional Sahel climate when SST anomalies in individual ocean basins and in land conditions combine synergistically to favor drought. This phenomenon has also been found in other parts of the world, such as East Asia and North America (Xue et al., 2016B).

Since SST effects and land forcing in the real world are likely smaller than specified in the WAMME II study, further investigations of the effects of aerosols as well as of other external forcings, such as greenhouse gases, and of atmospheric internal variability, are necessary, especially of their effect on the regional climate after the 1980s and for future projections. It is also shown that SST and land effects share many common characteristics in affecting the simulated Sahel precipitation decadal anomalies (Xue et al., 2016A). This raises the difficulty of separating the two effects locally in the real world. More comprehensive observational data and analyses with more components, plus modeling studies, should help to identify and improve understanding of the natural and anthropogenic causes and guide models’ development and improvement.

Mechanisms of Sahel L/A Interactions

Land-surface processes affect the surface water and energy balances that affect the atmosphere through the upward shortwave and longwave fluxes, sensible and latent heat fluxes, and momentum flux. Table 1 lists the changes of surface energy components and other variables after land degradation from the WAMME II LULCC experiment (Boone et al., 2016; Xue et al., 2016A).

Table 1. Surface Energy Balance Differences over the Land Degradation Area

	Albedo	SWD	SWU	CLD	LWD	LWU	Net Rad	LH	SH	Temperature
LULCC	~0.05	6.91	10.87	−0.03	−1.68	3.61	−9.25	−9.32	−0.23	0.50/0.96c

Note: 1) Units: surface temperature: K; Fluxes: w m^{-2}; 2) The meanings of abbreviations in the table are defined in the text; 3) Observation. This table is based on Xue et al., 2016A

The schematic diagram in Figure 8 shows the processes in the L/A interaction, with heavy lines outlining the major processes. Land-surface degradation in the Sahel increases the albedo. Upward shortwave radiation (SWU) from the surface is increased as a result of the higher albedo. This loss may be partially compensated for by increased incoming shortwave radiation (SWD), caused by less clouds (CLD) in a dry atmosphere. The net longwave radiation at the surface is reduced because the higher surface temperature increases outgoing longwave radiation (LWU). The reduced cloud and water vapor in the degradation simulations also reduce incoming longwave radiation (LWD) at the surface. However, the reductions of LWD and LWU are smaller compared with other energy components listed in Table 1. The total net radiation (Net RAD) is reduced.

The change in net radiation should be balanced by the change in surface heat fluxes. The changes in sensible heat flux (SH) are small. The latent heat flux (LH) in Table 1 is substantially lower, and this decrease is the main component to balance the energy loss due to less net radiation at the surface. Lower LAI and surface roughness length, higher stomatal resistance, and changes in other vegetation and soil properties in the degradation simulations all cause this reduction. Because of the large reduction in latent heat flux/evapotranspiration, less moisture is transferred to the atmosphere through the boundary layer, resulting in less convection and lower atmospheric heating rates at 500 mb, where the largest reduction occurs. The reduced total diabatic heating rate in the atmosphere is associated with relative subsidence, which in turn weakens the African monsoon flow and reduces moisture flux convergence, further reducing the atmospheric heating rate and leading to lower rainfall. More detailed calculation (Xue, 1997) shows that the dominant factor that caused relative diabatic cooling of the upper troposphere appears to be the reduction of convective heating rates as a result of reduced latent heat flux and moisture flux convergence. The change in radiative heating rate due to high surface albedo was a secondary factor, compared to the change in convective heating, although it may initiate other anomalous processes. Moreover, because the sum of the reduced latent heat flux and the sensible heat flux is lower than the reduced net radiation, the surface temperature increases.

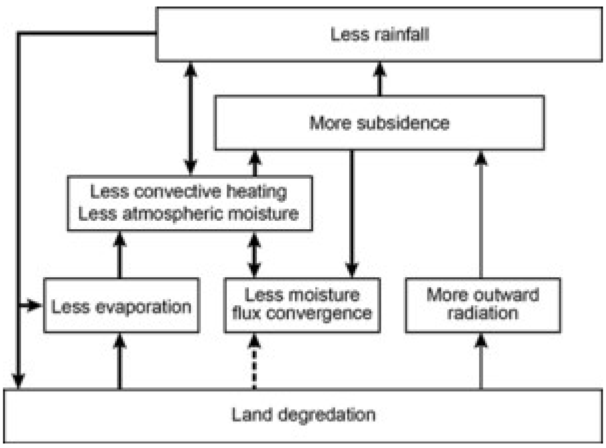

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Figure 8. Schematic diagram of land-surface degradation interactions and feedback processes. The dark lines represent the main processes. The dashed line between the surface and MFC indicates indirect interaction through modifying wind and atmospheric moisture fields.

Once rainfall is affected, additional feedbacks start playing a role. Reduced rainfall lessens soil moisture and then evaporation, producing a positive feedback. The feedback loops have different temporal scales associated with different "memory time scales" of the processes involved, from very fast response time scales, such as hours or less, to longer time scales, such as weeks to a season, which are likely associated with plant transpiration, subtracting the deeper soil moisture. For longer time scales, such as seasons to years, plant dynamics should play roles. When a drought is persistently long enough, the ecosystems may change (Xue et al., 2004A, 2016A). This brings up issues like ecosystem resilience, as explored by Wang and Eltahir (2000).

Early Sahel studies considered albedo to be the major factor causing the long-term drought, which raised controversies. In the experiments discussed above, the albedo changes were reasonable, less than 0.1—consistent with Nicholson et al.'s (1998) estimation. The latent heat flux reduction was dominant and led to surface warming. Moreover, the horizontal moisture flux divergence plays an important role, comparable with the change in surface evaporation (Xue et al., 2016A). With better land-surface parameterizations, all the controversies that were raised for the early Sahel L/A interaction studies have been properly addressed.

The mechanisms for land-surface/atmosphere interactions on an important WAM feature, the African Easterly Jet (AEJ), have also been examined by a number of studies. When the atmospheric temperatures below the mid-troposphere are higher to the north (i.e., over the Sahara) and lower to the south, meridional temperature gradients are positive over tropical West Africa and, according to atmospheric circulation thermodynamics principles, the thermal wind (and hence the jet) is easterly. The maximum latitudinal temperature gradient, which is related to the hot, dry surface conditions and a deep, well-mixed boundary layer in the Sahara heat low as well as cool, moist surface conditions associated with deep moist convection in the ITCZ, is associated with the strongest easterly thermal wind and therefore the AEJ in the mid-troposphere (Cook, 1999; Li et al., 2007; Thorncroft & Blackburn, 1999). Wu et al. (2009) suggest that it is not only the evaporation gradient that is highly correlated with soil moisture, but also a combination of vegetation properties and orography are essential for the maintenance of the mean climatological AEJ. Therefore, it is the very particular combination of moisture gradients, vegetation distribution, and orography that produces the AEJ, not the soil moisture gradients alone.

The WAMME studies further demonstrate the close relationship between the meridional thermal gradient, AEJ, and WAM precipitation and its onset. In the WAMME first experiment (Xue et al., 2010A), common empirical orthogonal functions (CEOF) analysis based on observational data and multimodel simulation results was applied to characterize the major WAM spatial and temporal features. CEOF analysis identified that the first principal component (PC1) of precipitation and PC1 and PC2 of surface temperature characterize the WAM precipitation evolution and the northward movement of the temperature gradient, respectively (Figure 9). The temperature PC1 that mostly covers the Sahara area between 20°N and 30°N and the temperature PC2 that mostly covers the Sahel area between 10°N and 20°N are defined as the Sahara mode and Sahel mode, respectively. The WAM precipitation northward movement/retreat is closely associated with the weakening/enhancing of the Sahel mode and the enhancing/weakening of the Sahara mode, which in turn enhances/weakens the meridional temperature gradient (Xue et al., 2010a). The speed of the WAM evolution and the position of the WAM precipitation band are closely related to the development of this thermal gradient. The study identifies a close relationship between WAM onset and thermal low development in the Sahara: the timing of monsoon onset is about 10–15 days after the peak of the Sahara mode.

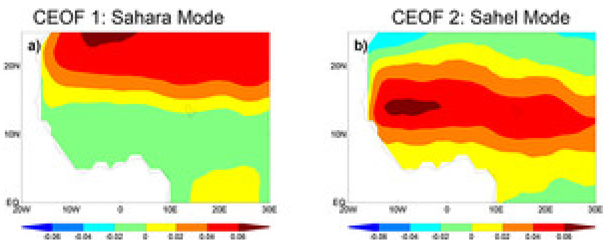

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Figure 9. (a) The temperature CEOF 1: Sahara mode. (b) The temperature CEOF 2: Sahel mode.

(Adapted from Xue et al., 2010a.)

The crucial role of the Sahara heat low that corresponds to the Sahara mode in WAM development has been extensively investigated and is well known (Biasutti et al., 2009; Evan et al., 2015; Lavaysse et al., 2009). The WAMME study reveals the important role of another mode, the Sahel mode. In the WAMME II experiment, the simulated rainfall reduction due to SST effects in the 1980s was associated with an enhanced Sahel mode and a weakened Sahara mode. The changes in the two modes were the results of the surface energy balance, which was closely related to the circulation/cloud cover change, and also provide a feedback to the changes in WAM precipitation evolution. In contrast with the SST effect, the changes in the Sahel mode of the surface temperature are dominant in the LULCC experiment. There is no noticeable change in the Sahara mode in the LULCC experiment (Xue et al., 2016a).

Mesoscale Circulation Variability and Land-Surface Processes in the Sahel

Observations indicate high spatial heterogeneity of surface vegetation and soil conditions in the Sahel area (Prince et al., 1995). The heterogeneity of vegetation distribution within a GCM grid box has not been taken into account in GCM simulations. Hutjes and Dolman (1999) found vegetation density variations to be a more dominant cause for variations in surface energy partitioning than soil moisture in certain cases. To solve the issue of vegetation heterogeneity, researchers have investigated issues of aggregation of surface characteristics. Based on a vegetation classification map with 30-m resolution, Shuttleworth et al. (1997) aggregated vegetation parameters to the model resolution of 2 km, using either those based on the dominant vegetation type or averaging each parameter appropriately weighted by subgrid relative areas of each vegetation class. Although either method produced similar domain-averaged heat fluxes, the variation in fluxes differed significantly. Only aggregated vegetation parameters could, at least qualitatively, reproduce observed rainfall.

Observational data also show that the Sahel rainfall anomalies have strong spatial heterogeneity, with many small peak cells (Xue et al., 2016A). This feature has been confirmed by analysis based on rain gauge data, and the small cells may reflect the natural variability of mesoscale convective activity (Le Barbé et al., 2002), which is missed in GCM studies due to the GCMs’ relatively coarse resolution. Observational evidence suggests L/A interactions at local scales could be much stronger and more localized than the large-scale average. Taylor and Lebel (1998) found strong positive correlation between daily and antecedent rainfall at a range of time scales. In semi-arid regions this mechanism may lead to preferred and seasonally persistent rainfall patterns. It is found that as intense storms pass over areas of marked gradients in evaporation, antecedent rainfall shows a particularly strong effect on storm development.

The AMMA data have been applied to investigate how this heterogeneity influences the development of convective storms over the course of the diurnal cycle. The surface processes are strongly influenced by the availability of surface soil moisture due to high evapotranspiration demand and the sparse vegetation across the Sahel, particularly in the early wet season (Kohler et al., 2010). Rain events create strong mesoscale variability in soil moisture, and the resulting patterns of sensible and latent heating have been found to play an important role in the development of new storms during the afternoon in a number of studies. Taylor et al. (2007) used land-surface temperature information from satellite data as a proxy for soil moisture (wet surfaces are up to 10 ºC cooler than dry surfaces) as well as AMMA aircraft flight measurements over areas containing wet and dry soils for their analyses and found that the temperature within the convective boundary layer during the afternoon was significantly correlated with the land-surface temperature (also soil moisture) for surface features as small as 2.5 km. Furthermore, there was a clear correlation between surface-induced temperature gradients and the low-level winds, which is evidence for mesoscale circulation change induced by land-surface conditions (Garcia-Carreras et al., 2010).

Numerical model experiments have shown how surface-driven convergence provides a favored location for the initiation of deep convection (Gaertner et al., 2010; Gantner & Kalthoff, 2010). The importance of this feedback mechanism has been highlighted by Taylor et al. (2011B), who examined the atmospheric impact of soil moisture on space scales of 5 km upward and time scales of several days. After analyzing nearly 4,000 storms from satellite data of clouds and antecedent land-surface temperature, including detailed tracking of mesoscale convective systems (MCS), the investigators evaluated the relationship between the spatial structure of soil moisture and the probability of convective storm initiation (Taylor et al., 2011A). In comparison to the case of a homogeneous surface, storm initiation was twice as likely to occur 10 km upwind of a transition from dry to wet soils, consistent with other studies (Gaertner et al., 2010; Gantner and Kalthoff, 2010). Contrasts forcing creates maximum low-level convergence where the surface-driven component opposes the large-scale flow (Figure 10). This effect was important for 1 in 8 MCS initiations in the region. Storms tend to initiate over dry soil, but the occurrence of previous rain to create the heterogeneity is a prerequisite for this feedback. The MCS then travel, often many hundreds of kilometers, in turn creating new heterogeneity and favoring more initiations in subsequent days, a positive feedback on the scale of MCS, ~100 km.

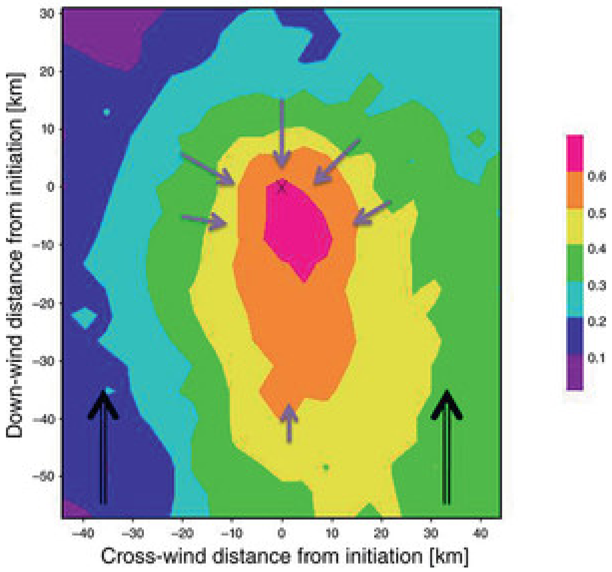

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Figure 10. Favored location (X) for initiation of convective storms. Storms tend to develop over locally warm surfaces (shading denotes land-surface temperature anomalies in ºC based on a composite of nearly 4,000 cases), but close to wetter (cooler) soils down wind. Arrows in mauve and black denote the

surface-induced and large-scale components of the wind, respectively.

Adapted from Xue et al. (2012), which is based on Taylor et al. (2011A).

Once MCS have developed, various processes may influence the strength, and even the sign, of feedbacks between soil moisture and individual storms. Gantner and Kalthoff (2010) show that mature MCS with well-developed gust fronts can intensify over wet soils due to increased convective available potential energy, consistent with an observational case study from AMMA (Kohler et al., 2010). However, this positive feedback may reverse, depending on the phase of the diurnal cycle, the convective inhibition and synoptic state, and the scale and orientation of the wet patch relative to the large-scale flow (Gaertner et al., 2010).

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References

Alexandre, A., Meunier J.-D., Lezine, A.-M., Vincerns, A., & Schwartz, D. (1997). Phytoliths: indicators of grassland dynamics during the late Holocene in intertropical Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *136*, 213–229.

Alter, R. E., Im, E.-S., & Eltahir, E. A. B. (2015). **Rainfall consistently enhanced around the Gezira Scheme in East Africa due to irrigation**. *Nature Geoscience*, *8*, 763–767.

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*, 3471–3486.

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

Boone, A., De Rosnay, P., Basalmo, G., Beljaars, A., Chopin, F., Decharme, B., Delire, C., Ducharne, A., Gascoin, S., Guichard, F., Gusev, Y., Harris, P., Jarlan, L., Kergoat, L., Mougin, E., Nasonova, O., Norgaard, A., Orgeval, T., Ottlé, C., Poccard-Leclercq, I., Polcher, J., Sandholt, I., Saux-Picart, S., Taylor, C., & Xue, Y. (2009). **The AMMA land surface model intercomparison project**. *Bulletin of the American Meteorological Society*, *90*, 1865–1880.

Boone, A., Poccard-Leclerq, I., Xue, Y., Feng, J., & De Rosnay, P. (2010). **Evaluation of the WAMME model surface fluxes using results from the AMMA land-surface model intercomparison project**. *Climate Dynamics*, *35*, 127–142.

Boone, A., Xue, Y., De Sales, F., Comer, R., Hagos, S., Mahanama, S., Schiro, K., Song, G., Wang, G., Li, S., & Mechoso, C. R. (2016). **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*, 3547–3573.

Braconnot, P., Joussaume, S., de Noblet, N., & Ramstein G. (2000). Mid-Holocene and Last Glacial Maximum African monsoon changes as simulated within the Paleoclimate Modelling Intercomparison Project. *Global and Planetary Change*, *26*, 51–66.

Charney, J. G. (1975). Dynamics of deserts and drought in the Sahel. *Quarterly Journal of the Royal Meteorological Society*, *101*, 193–202.

Charney, J. G., Quirk, W. K., Chow, S.-H., & Kornfield, J. (1977). A comparative study of the effects of albedo change on drought in semi-arid regions. *Journal of the Atmospheric Sciences*, *34*, 1366–1385.

Clark, D., Xue, Y., Valdes, P., & Harding R. (2001). Impact of land surface degradation over different subregions in Sahel on climate in tropical North Africa. *Journal of Climate*, *14*, 1809–1822.

Claussen, M., & Gayler, V. (1997). The greening of the Sahara during the mid-Holocene: Results of an interactive atmosphere-biome model. *Global Ecology and Biogeography Letters*, *6*, 369–377.

Claussen, M., Kubatzki, C., Brovkin, V., Ganopolski, A., Hoelzmann, P., & Pachur, H. J. (1999). Simulation of an abrupt change in Saharan vegetation at the end of the mid-Holocene. *Geophysical Research Letters*, *26*, 2037–2040.

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

Courel, M. F., Kandel, R. S., & Rasool, S. I. (1984). Surface albedo and the Sahel drought. *Nature*, *307*, 528–531.

De Rosnay, P., Drusch, M., Boone, A., Balsamo, G., Decharme, B., Harris, P., Kerr, Y., Pellarin, T., Polcher, J., Wigneron, J.-P. (2009). **AMMA Land Surface Model Intercomparison Experiment coupled to the Community Microwave Emission Model: ALMIP-MEM**. *Journal of Geophysical Research*, *114*, D05108.

De Sales, F., Xue, Y., & Okin, G. S. (2016). **Impact of burned area on the northern African seasonal climate from the perspective of regional modelling**. *Climate Dynamics*. 47, 3393–3413.

D’Odorico, P., Bhattachan, A., Davis, K. F., Ravi, S., & Runyan, C. W. (2013). Global desertification: Drivers and feedbacks. *Advances in Water Resources*, *51*, 326–344.

Douville, H., Conil, S., Tyteca, S., & Voldoire, A. (2007). **Soil moisture memory and West African monsoon predictability: Artefact or reality?** *Climate Dynamics*, *28*, 723–742.

Dregne, H. E., & Chou, N. T. (1992). *Global desertification dimensions and costs*. In *Degradation and restoration of arid lands*. Lubbock: Texas Tech. University.

Druyan, L. M., Feng, J., Cook, K. H., Xue, Y., Fulakeza, M., Hagos, S. M., Konare, A., Moufouma-Okia, W., Rowell, D. P., & Vizy, E. K., & Sanda Ibrah, S. (2010). **The WAMME regional model intercomparison study**. *Climate Dynamics*, *35*, 175–192.

Eklundh, L., & Olsson, L. (2003). **Vegetation index trends for the African Sahel 1982–1999**. *Geophysical Research Letters*, *30*, 1430.

Evan, A. T., Flament, C., Lavaysse, C., Kosha, C., & Saci, A. (2015). Water vapor–forced greenhouse warming over the Sahara Desert and the recent recovery from the Sahelian drought. *Journal of Climate*, *28*, 108–123.

Folland, C. K., Palmer, T. N., & Parker, D. E. (1986). **Sahel rainfall and worldwide sea temperatures, 1901–85**. *Nature*, *320*, 602–607.

Fu, C., Yasunari, T., & Lütkemeier, S. (2004). The Asian monsoon climate. In P. Kabat et al. (Eds.), *Vegetation, water, humans and the climate* (pp. 115–127). Berlin: Springer-Verlag.

Gaertner, M. A., Dominguez, M., & Garvert, M. (2010). **A modelling case-study of soil moisture-atmosphere coupling**. *Quarterly Journal of the Royal Meteorological Society*, *136*, 483–495.

Gantner, L., & Kalthoff, N. (2010). **Sensitivity of a modelled life cycle of a mesoscale convective system to soil conditions over West Africa**. *Quarterly Journal of the Royal Meteorological Society*, *136*, 471–482.

Garcia-Carreras, L., Parker, D. J., Taylor, C. M., Reeves, C. E., & Murphy, J. G. (2010). **Impact of mesoscale vegetation heterogeneities on the dynamical and thermodynamic properties of the planetary boundary layer**. *Journal of Geophysical Research: Atmospheres*, *115*. D03102.

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

Goldewijk, K. K. (2001). Estimating global land use change over the past 300 years: The HYDE database. *Global Biogeochemical Cycles*, *15*, 417–433.

Govaerts, Y. M., & Lattanzio, A. (2008). **Estimation of surface albedo increase during the eighties Sahel drought from Meteosat observations**. *Global and Planetary Change*, *64*, 139–145.

Grippa, M., Kergoat, L., Frappart, F., Araud, Q., Boone, A., De Rosnay, P., Lemoine, J.-M., Gascoin, S., Balsamo, G., Ottlé, C., Decharme, B., Saux-Picart, S., & Ramillien, G. (2011). **Land water storage changes over West Africa estimated by GRACE and land surface models**. *Water Resources Research*, *47*, W05549.

Hastenrath, S., & Lamb, P. J. (1977). **Some aspects of circulation and climate over the eastern equatorial Atlantic**. *Monthly Weather Review*, *105*, 1019–1023.

He, Y., & Lee, E. (2016). Empirical relationships of sea surface temperature and vegetation activity with summer rainfall variability over the Sahel. *Earth Interactions*, *20*, 6.

Hiernaux, P., Diarra, L., Trichon, V., Mougin, E., Soumaguel, N., & Baup, F. (2009). Woody plant population dynamics in response to climate changes from 1984 to 2006 in Sahel (Gourma, Mali). *Journal of Hydrology*, *375*, 103–113.

Hulme, M. (1994). Validation of large-scale precipitation fields in general circulation models. In M. Desbois & F. Desalmand (Eds.), *Global precipitations and climate change*. NATO ASI Series. Berlin: Springer-Verlag.

Hurtt, G. C., Chini, L. P., Frolking, S., Betts, R., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Goldewijk, K. K., Riah, K. (2011). **Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands**. *Climatic Change*, *109*, 117–161.

Hurtt, G. C., Frolking, S., Fearon, M. G., Moore, B., Shevliakova, E., Malyshev, S., Pecala, S. W., & Houghton, R. A. (2006). The underpinnings of land-use history: Three centuries of global gridded land-use transitions, wood harvest activity, and resulting secondary lands. *Global Change Biology*, *12*, 1208–1229.

Hutjes, R. W. A., & Dolman, A. J. (1999). The effects of subgrid variability in vegetation cover and soil moisture on regional scale weather: A case study for the Sahel. In R. Harding et al. (Eds.), *Modelling the effect of land degradation on climate. Climate and land degradation first annual report*. Centre for Ecology and Hydrology, Wallingford, U.K.

Janicot, S., Moron, V., & Fontaine, B. (1996). **ENSO dynamics and Sahel droughts**. *Geophysical Research Letters*, *23*, 515–518.

Kang, H.-S., Xue, Y., & Collatz, G. J. (2007). Assessment of satellite-derived leaf area index datasets using a general circulation model: Seasonal variability. *Journal of Climate*, *20*, 993–1015.

Kitoh, A., Yamazaki, K., & Tokioka, T. (1988). Influence of soil moisture and surface albedo changes over the African tropical rain forest on summer climate investigated with the MRI-GCM-I. *Journal of Meteorological Society of Japan*, *66*, 65–85.

Knight, J. R, Allan, R. J., Folland, C. K., Vellinga, M., & Mann, M. E. (2005). **A signature of persistent natural thermohaline circulation cycles in observed climate**. *Geophysical Research Letters*, *32*, L20708.

Kohler, M., Kalthoff, N., & Kottmeier, C. (2010). **The impact of soil moisture modifications on CBL characteristics in West Africa: A case-study from the AMMA campaign**. *Quarterly Journal of the Royal Meteorological Society*, *136*, 442–455.

Koster, R. D., Dirmeyer, P. A., Guo, Z., Bonan, G., Chan, E., Cox, P., Gordon, C. T., Kanae, S., Kowalczyk, E., Lawrence, D., Liu, P., Lu, C-H., Malyshev, S., McAvaney, B., Mitchell, K., Mocko, D., Oki, T., Oleson, K., Pitman, A., Sud, Y. C., Taylor, C. M., Verseghy, D., Vasic, R., Xue, Y., & Yamada, T. (2004). Regions of strong coupling between soil moisture and precipitation. *Science*, *305*, 1138–1140.

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

Lau, K. M., Shen, S. S. P., Kim, K. M., & Wang, H. (2006). **A multimodel study of the twentieth-century simulations of Sahel drought from the 1970s to 1990s**. *Journal of Geophysical Research*, *111*, D07111.

Laval, K., & Picon, L. (1986). Effect of a change of the surface albedo of the Sahel on climate. *Journal of the Atmospheric Sciences*, *43*, 2418–2429.

Lavaysse, C., Flamant, C., Janicot, S., Parker, D. J., Lafore, J. P., Sultan, B., & Pelon J. (2009). Seasonal evolution of the West African heat low: A climatological perspective. *Climate Dynamics*, *33*, 313–330.

Le Barbé, L. L., Lebel, T., & Tapsoba, D. (2002). Rainfall variability in West Africa during the years 1950–90. *Journal of Climate*, *15*, 187–202.

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

Lebel, T., Parker, D. J., Flamant, C., Höller, H., Polcher, J., Redelsperger, J.-L., Thorncroft, C., Bock, O., Bourles, B., Galle, S., Marticorena, B., Mougin, E., Peugeot, C., Cappelaere, B., Descroix, L., Diedhiou, A., & Gaye, A. (2011). The AMMA field campaigns: Accomplishments and lessons learned. *Atmospheric Science Letters*, *12*, 123–128.

Li, W.-P., Xue, Y., & Poccard, I. (2007). Numerical investigation of the impact of vegetation indices on the variability of West African summer monsoon. *Journal of Meteorological Society of Japan*, *85A*, 363–383.

Liu, Z., Notaro, M., Kutzbach J., & Liu, N. (2006) An observational assessment of global vegetation–climate feedbacks. *Journal of Climate*, *19*, 787–814.

Los, S. O., Weedon, G. P., North, P. R. J., Kaduk, J. D., Taylor, C. M., & Cox, P. M. (2006). **An observation-based estimate of the strength of rainfall-vegetation interactions in the Sahel**. *Geophysical Research Letters*, *33*, L16402.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., & Francis, R. C. (1997). **A Pacific interdecadal climate oscillation with impacts on salmon production**. *Bulletin of the American Meteorological Society*, *78*, 1069–1079.

Martiny, N., Richard, Y., & Camberlin, P. (2005). **Interannual persistence effects in vegetation dynamics of semi-arid Africa**. *Geophysical Research Letters*, *32*, L24403.

Mohino, E., Janicot, S., & Bader, J. (2011). **Sahelian rainfall and decadal to multidecadal SST variability**. *Climate Dynamics*, *37*, 419–440.

New, M., Hulme, M., & Jones, P. D. (1999). Representing twentieth century space-time climate variability. Part 1: Development of a 1961–90 mean monthly terrestrial climatology. *Journal of Climate*, *12*, 829–856.

Nicholson, S. E., Dezfuli, A. K., & Klotter, D. (2012). **A two-century precipitation dataset for the continent of Africa**. *Bulletin of the American Meteorological Society*, *93*, 1219–1231.

Nicholson, S. E., Tucker, C. J., & Ba, M. B. (1998). Desertification, drought, and surface vegetation: An example from the West African Sahel. *Bulletin of the American Meteorological Society*, *79*, 815–829.

Nobre, C. A., Silva Dias, M. A., Culf, A. D., Polcher J., Gash, J. H. C., Marengo, J. A., & Avissar R. (2004). The Amazon climate. In P. Kabat et al. (Eds.), *Vegetation, water, humans and the climate* (pp. 79–92). Berlin: Springer-Verlag.

Norton, C. C., Mosher, F. R., & Hinton, B. (1979). An investigation of surface albedo variations during the recent Sahel drought. *Journal of Applied Meteorology*, *18*, 1252–1262.

Prince, S. D., Kerr, Y. H., Goutorbe, J.-P., Lebel, T., Tinga, A., Bessemoulin, P., Brouwer, J., Dolman, A. J., Engman, E. T., Gash, J. H. C., Hoepffner, M., Kabat, P., Monteny, B., Said, F., Sellers, P., & Wallace, J. S. (1995). Geographical, biological and remote sensing aspects of the hydrologic atmospheric pilot experiment in the Sahel (HAPEX-Sahel). *Remote Sensing of Environment*, *51*, 215–234.

Ramankutty, N., & Foley, J. A. (1999). Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Global Biogeochemical Cycles*, *13*, 997–1027.

Redelsperger, J. L., Thorncroft, C. D., Diedhiou, A., Lebel, T., Parker, D. J., & Polcher, J. (2007). American monsoon multidisciplinary analysis. *Bulletin of the American Meteorological Society*, *88*, 1740–1746.

Ripley, E. A. (1976). Drought in the Sahara: Insufficient biogeophysical feedback? *Science*, *191*, 100–101.

Rodriguez-Fonseca, B., Mohino, E., Mechoso, C. R., Caminade, C., Biasutti, M., Gaetani, M., Garcia-Serrano, J., Vizy, E.K., Cook, K., Xue, Y., Polo, I., Losada, T., Druyan, L., Fontaine, B., Bader, J., Doblas-Reyes, F. J., Goddard, L., Janicot, S., Arribas, A., Lau, W., Colman, A., Vellinga, M., Rowell, D. P., Kucharski, F., & Voldoire, A. (2015). Variability and predictability of West African droughts. *Journal of Climate*, *28*, 4034–4060.

Rodwell, M. J., & Hoskins, B. J. (1996). Monsoons and the dynamics of deserts. *Quarterly Journal of the Royal Meteorological Society*, *122*, 1385–1404.

Rowell, D. P. (2003). **The impact of Mediterranean SSTs on the Sahelian rainfall season**. *Journal of Climate*, *16*, 849–862.

Saltzmann, U., & Martyn, W. (1998). The Holocene vegetational history of the Nigerian Sahel based on multiple pollen profiles. *Review of Palaeobotany and Palynology*, *100*, 39–72.

Shinoda, M., & Yamaguchi, Y. (2003). Influence of soil moisture anomaly on temperature in the Sahel: A comparison between wet and dry decades. *Journal of Hydrometeorology*, *4*, 437–447.

Shuttleworth, W. J., Yang, Z.-L., & Arain, M. A. (1997). Aggregation rules for surface parameters in global models. *Hydrology & Earth System Science*, *2*, 217–226.

Snyder, P. K. (2010). The influence of tropical deforestation on the Northern Hemisphere climate by atmospheric teleconnections. *Earth Interact*, *14*, 1–34.

Steiner, A., Pal, J., Rauscher, S., Bell, J., Diffenbaugh, N., Boone, A., Sloan, L. C., & Giorgi, F. (2009). **Land surface coupling in regional climate simulations of the West African monsoon**. *Climate Dynamics*, 33, 869–892.

Sud, Y. C., & Fennessy, M. (1982). A study of the influence of surface albedo on July circulation in semiarid regions using the GLAS GCM. *Journal of Climatology*, *2*, 105–125.

Sud, Y. C., Shukla, J., & Mintz, Y. (1988). Influence of land surface roughness on atmospheric circulation and precipitation: A sensitivity study with a general circulation model. *Journal of Climate*, *27*, 1036–1054.

Taylor, C. M. (2008). Intraseasonal land-atmosphere coupling in the West African monsoon. *Journal of Climate*, *21*, 6636–6648.

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

Taylor, C. M., & Lebel, T. (1998). Observational evidence of persistent convective-scale rainfall patterns. *Monthly Weather Review*, *126*, 1597–1607.

Taylor, C. M., Parker, D. J., & Harris, P. P. (2007). An observational case study of mesoscale atmospheric circulations induced by soil moisture. *Geophysical Research Letters*, *34*, L15801.

Taylor, C. M., Parker, D. J., Kalthoff, N., Gaertner, M. A., Philippon, N., Bastin, S., Harris, P. P., Boone, A., Guichard, F., Agusti-Panareda, A., Baldi, M., Cerlini, P., Descroix, L., Douville, H., Flamant, C., Grandpeix, J. Y., & Polcher, J. (2011b). New perspectives on land–atmosphere feedbacks from the African Monsoon Multidisciplinary Analysis. *Atmospheric Science Letters*, *12*, 38–44.

Thorncroft, C. D., & Blackburn, M. (1999). Maintenance of the African easterly jet. *Quarterly Journal of the Royal Meteorological Society*, *125*, 763–786.

Vizy, E. K., & Cook, K. H. (2002). **Development and application of a mesoscale climate model for the tropics: Influence of sea surface temperature anomalies on the West African monsoon**. *Journal of Geophysical Research*, *107*(D3), 4023.

Voldoire, A., & Royer, J. F. (2004). Tropical deforestation and climate variability. *Climate Dynamics*, *22*, 857–874.

Walker, J., & Rowntree, P. R. (1977). The effect of soil moisture on circulation and rainfall in a tropical model. *Quarterly Journal of the Royal Meteorological Society*, *103*, 29–46.

Waller, M. P., Street-Perrott, F. A., & Wang, H. (2007). Holocene vegetation history of the Sahel: Pollen, sedimentological and geochemical data from Jikariya Lake, north-eastern Nigeria. *Journal of Biogeography*, *34*, 1575–1590.

Wang, G., & Eltahir, E. A. B. (2000). Biosphere-atmosphere interactions over West Africa. II: Multiple climate equilibria. *Quarterly Journal of the Royal Meteorological Society*, *126*, 1261–1280.

Wang, G. L., Eltahir, E. A. B., Foley, J. A., Pollard, D., & Levis, S. (2004). **Decadal variability of rainfall in the Sahel: Results from the coupled GENESIS-IBIS atmosphere-biosphere model**. *Climate Dynamics*, *22*, 625–637.

Wu, M.-L. C., Reale, O., Schubert, S. D., Suarez, M. J., Koster, R. D., & Pegion, P. J. (2009). African Easterly jet: Structure and maintenance. *Journal of Climate*, *22*, 4459–4479.

Xue, Y. (1997). Biosphere feedback on regional climate in tropical North Africa. *Quarterly Journal of the Royal Meteorological Society*, *123*, 1483–1515.

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*, 748921.

Xue, Y., De Sales, F., Lau, K. M. W., Boone, A., Feng, J., Dirmeyer, P., Guo, Z. C., Kim, K. M., Kitoh, A., Kumar, V., Poccard-Leclercq, I., Mahowald, N., Moufouma-Okia, W., Pegion, P., Rowell, D. P., Schemm, J., Schubert, S., Sealy, A., Thiaw, W. M., Vintzileos, A., Williams, S. F., & Wu, M. L. (2010a). **Intercomparison and analyses of the climatology of the West African monsoon in the West African Monsoon Modeling and Evaluation Project (WAMME) First Model Intercomparison Experiment**. *Climate Dynamics*, *35*, 3–27.

Xue, Y., De Sales, F., Lau, W. K.-M., Boone, A., Kim, K.-M., Mechoso, C. R., Wang, G., Kucharski, F., Schiro, K., Hosaka, M., Li, S., Druyan, L. M., Seidou Sanda, I., Thiaw, W., Zeng, N., Comer, R. E., Lim, Y.-K., Mahanama, S., Song, G., Gu, Y., Hagos, S. M., Chin, M., Schubert, S., Dirmeyer, P., Leung, L. R., Kalnay, E., Kitoh, A., Lu, C.-H., Mahowald, N. M., & Zhang, Z. (2016a). **West African monsoon decadal variability and drought and surface-related forcings: Second West African Monsoon Modeling and Evaluation Project Experiment (WAMME II)**. *Climate Dynamics*, *47*, 3517–3545.

Xue, Y., De Sales, F., Vasic, R., Mechoso, C. R., Prince, S. D., & Arakawa, A. (2010b). Global and temporal characteristics of seasonal climate/vegetation biophysical process (VBP) interactions. *Journal of Climate*, *23*, 1411–1433.

Xue, Y., Hutjes, R. W. A., Harding, R. J., Claussen, M., Prince, S., Lambin, E. F., Allen, S. J., Dirmeyer, P., & Oki, T. (2004a). The Sahelian Climate (Chapter A5). In P. Kabat et al. (Eds.), *Vegetation, Water, Humans and the Climate* (pp. 59–77). Berlin: Springer-Verlag.

Xue, Y., Juang, H.-M. H., Li, W., Prince, S., DeFries, R., Jiao, Y., & Vasic, R. (2004b). **Role of land surface processes in monsoon development: East Asia and West Africa**. *Journal of Geophysical Research*, *109*, D03105.

Xue, Y., Liou, K.-N., & Kasahara, A. (1990). Investigation of the biophysical feedback on the African climate using a two-dimensional model. *Journal of Climate*, *3*, 337–352.

Xue, Y., Oaida, C. M., Diallo, I., Neelin, J. D., Li, S., De Sales, F., … Yi, L. (2016b). **Spring land temperature anomalies in northwestern US and the summer drought over Southern Plains and adjacent areas**. *Environmental Research Letters*, *11*, 044018.

Xue, Y., & Shukla, J. (1993). The influence of land surface properties on Sahel climate. Part I: Desertification. *Journal of Climate*, *6*, 2232–2245.

Xue, Y., & Shukla, J. (1996). The influence of land surface properties on Sahel climate. Part II: Afforestation. *Journal of Climate*, *9*, 3260–3275.

Zeng, N., Neelin, J. D., Lau, W. K.-M., & Tucker, C. J. (1999). Vegetation-climate interaction and Sahel climate variability. *Science*, *286*, 1537–1540.

Zhang, Y., Wallace, J. M., & Battisti, D. S. (1997). **ENSO-like interdecadal variability: 1900–93**. *Journal of Climate*, *10*, 1004–1020.

Yongkang Xue

Department of Geography, University of California, Los Angeles