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Assessment of uncertainties in the response of the African monsoon precipitation to land use change simulated by a regional model

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Abstract Land use and land cover (LULC) over Africa have changed substantially over the last 60 years and this change has been proposed to affect monsoon circulation and precipitation. This study examines the uncertainties of model simulated response in the African monsoon system and Sahel precipitation due to LULC change using a set of regional model simulations with different combinations of land surface and cumulus parameterization schemes. Although the magnitude of the response covers a broad range of values, most of the simulations show a decline in Sahel precipitation due to the expansion of pasture and croplands at the expense of trees and shrubs and an increase in surface air temperature. The relationship between the model responses to LULC change and the climatologists of the control simulations is also examined. Simulations that are climatologically too dry or too wet compared to observations and reanalyses have weak response to land use change because they are in moisture or energy limited regimes respectively. The ones that lie in between have stronger response to the LULC changes, showing a more significant role in land–atmosphere interactions. Much of the change in precipitation is related to changes in circulation, particularly to the response of the intensity and latitudinal position of the African Easterly Jet, which varies with the changes in meridional surface temperature gradients. The study highlights the need for measurements of the surface fluxes across the meridional cross-section of the Sahel to evaluate models and thereby allowing human impacts such as land use change on the monsoon to be projected more realistically.

Keywords African monsoon · Land use change · Land cover change · African Easterly Jet · Land degradation · Crop land · Pasture land · Regional model simulations · Land surface models

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1 Introduction

The African Sahel has experienced major decadal climatic swings since the middle of the twentieth century with lasting socio-economic consequences. These variations have been attributed primarily to global sea surface temperature (SST) variations (Giannini et al. 2003; Hagos and Cook 2008). However, they also coincide with a period of rapid population growth and associated changes in land use. The United Nations Environmental Program (Kandji 2006) estimated that the population of the region has been doubling every 20 years. This 3 % per year increase outstrips the annual rate of increase of food production (2 %), which is manifested by the doubling of harvested area over the last 60 years. Furthermore poor land management practices such as overgrazing and cutting of trees for firewood are known to have led to soil erosion and further land surface degradation (Reynolds et al. 2007).

The potential feedback of land-use change on the African monsoon precipitation has been an area of active research since the mid 1970s. Charney (1975) suggested that the African monsoon circulation is closely tied to the albedo gradient between vegetation and bare soil. He argued that a reduction in the coverage of the former in favor of the latter would increase atmospheric subsidence and weaken the monsoon precipitation, which in turn could lead to further land degradation. Other modeling studies indicate that such mechanism might even be responsible for the relatively rapid transition of the Sahara from a savanna to desert during the mid-Holocene period (Claussen et al. 1999; Patricola and Cook 2008). Given the rapid expansion of agriculture over the last 60 years, a similar interaction of human induced land degradation with monsoon precipitation is not inconceivable. In fact, several model simulation studies that prescribe artificially degraded land-cover generally show decreased precipitation. The extent of the response in models, however, is quite sensitive to the treatment of land surface processes in the models and the estimate of the degradation, which itself is uncertain. Many of the earlier studies tended to be more idealized or the imposed land-cover changes were generally idealized to provide qualitative estimates of the precipitation response (e.g. Zheng and Eltahir 1997; Xue 1997). More recently however the need for quantitatively assessing the impact of land-use change to better understand the relative role of SST and land cover/land use change on the African climate has been recognized.

A GCM study involving a realistic estimate of land use change showed that in comparison to the 1,961 conditions, the simulated rainfall decreases by 4.6 % (1996) and 8.7 % (2015) in response to land degradation (Taylor et al. 2002). They found that the decreases are related to the late onset of the monsoon. In a similar study, using the International Center for Theoretical Physics (ICTP) regional climate model RegCM, Abiodun et al. (2008) showed that extreme deforestation and desertification reduced precipitation because the easterlies that drove moisture away from the Sahel region were enhanced by the increased surface temperature. While their study provides insight into the mechanism of the interaction of land-use change with the African monsoon, they acknowledge that the prescribed land use change and hence the precipitation response they found are likely exaggerated. A multi-model study of attribution of variability of precipitation in the late twentieth century by Lau et al. (2006) showed that models that capture the observed precipitation variability also showed robust land surface feedbacks with strong sensitivity of precipitation and land evapotranspiration (ET) to soil moisture. Another GCM study (Kucharski et al. 2013) suggests that the decadal variability in precipitation, which is primarily driven by SST variability, is significantly enhanced by land surface albedo feedbacks through the mechanisms similar to that proposed by Charney et al. (1977).

In this study, uncertainty in regional model simulated monsoon precipitation to land-use change over the last 60 years is examined. We used ensembles of regional model experiments with various land surface and cumulus parameterization schemes to explore model uncertainties. The relationships between the responses of the ensemble members and their respective climatologists (in the control simulations) are assessed.

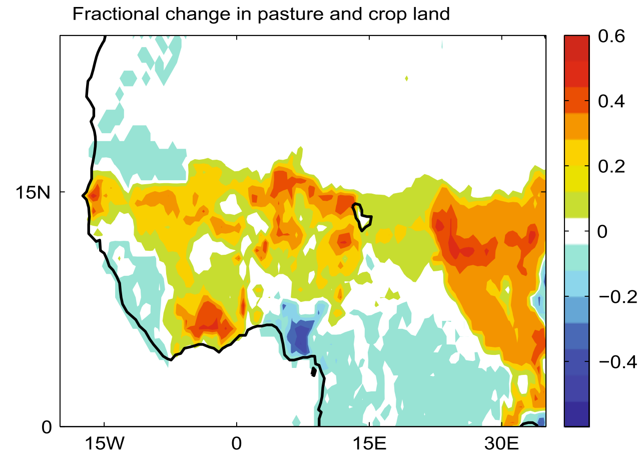

Fig. 1 Estimate of fractional change in crop and pasture land over the last 60 years (Hurtt et al. 2011)

2 Model and simulation design

2.1 Estimate of land-use change and application to the regional model

The design of the land use and land cover change in this experiment is based on the West African Monsoon Modeling and Evaluation Project (WAMME, Xue et al. 2010) experiment II, which aims to examine the response of the West African climate to sea surface temperature, land use/land cover (LULC) change, and aerosol forcing. The global 0.5° gridded estimates of annual land-use transition product from Hurtt et al. (2011) is used to derive the transition of forest land to pasture or cropland in the Sahel region. This dataset was created based on the global land-use history products—the History Database of the Global Environment (HYDE, Klein Goldewijk 2001). The input to the model includes national data from the U.N. Food and Agricultural Organization (FAO 2008) and other census data along with satellite derived land cover. Figure 1 shows the fractional change for crop and pasture land between 1950 and 2010 obtained from the Hurtt et al. dataset.

In designing the land-use change experiments with the Advanced Research Weather Research and Forecasting model ARWRF V3.4 (Skamarock et al. 2008), model grid points that are prescribed shrubland, grassland, and woodland are prescribed with barren/sparse vegetation. Similarly, model grid points that are prescribed savanna are

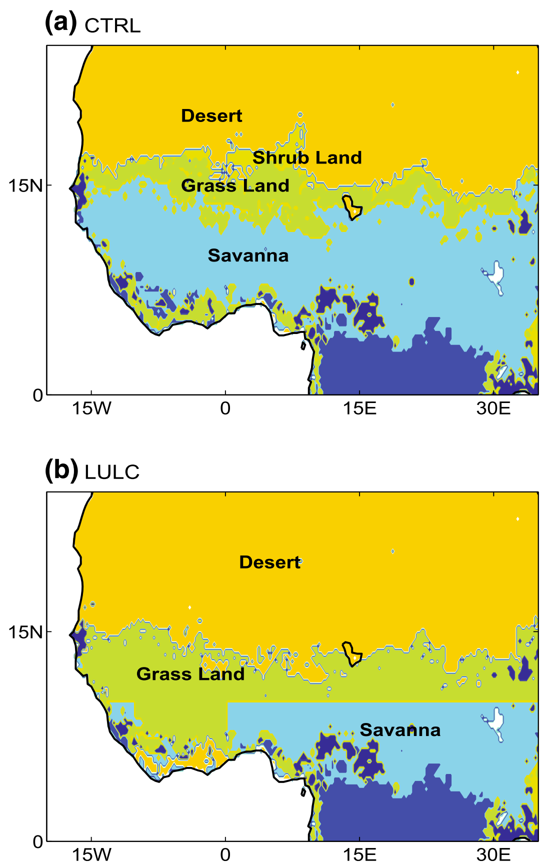

Fig. 2 **a** prescribed land use for CTRL simulations and **b** LULC simulations

changed to grassland, and coastal evergreen broadleaf is changed to savanna. This maintains the meridional gradient of the vegetation cover but a large gradient of land cover change appears in the south compared to the map in the control run. These prescribed changes to model land-use classes are shown in Fig. 2. These land use changes include corresponding changes in surface albedo, green fraction and emissivity.

2.2 Experiments

We perform 16 CTRL and 16 LULC simulations. In the LULC cases, the land cover conditions are modified as discussed above. The 16 simulations correspond to different combinations of land surface schemes selected from NOAH, SSIB and PLEIM-XIU, and cumulus parameterization schemes selected from six available options in WRF. The same changes in surface albedo, green fraction, and emissivity are prescribed regardless of the land surface schemes used. Of the 18 combinations of three land surface and six cumulus parameterization schemes, two simulations (NOAH with Kain-Frisch and Pleim-Xiu with Kain-Frisch) produced unrealistically large mean precipitation so they are excluded from further analysis. The overall design of the simulations and the choices of parameterization are summarized on Table 1. The NCEP-DOE global reanalysis (Kanamitsu et al. 2002) is used to provide initial, lateral and surface boundary conditions. The domain extends from 35°W to 35°E zonally and 35°S and 35°N in the meridional direction, so it includes the entire continent of Africa except the Horn region and the tropical Atlantic Ocean to the northeastern tip of Brazil. The SST and lateral boundary conditions are updated every 6 h. The simulations start on the 1st of January 2001 and run for 1 year in order to provide sufficient spin-up period even though our analysis focuses on summer (JJAS) precipitation and circulations. Several studies (Seneviratne and Koster 2012; Moufouma-Okia and Rowell 2010 and references therein) have shown that the atmospheric response to soil moisture has a relatively short memory, that 6 months spin-up period is sufficient for the model to "forget" the fact that the two sets of simulations have the same soil moisture initialization.

Table 1 Model setup

Common to all simulations	
Simulation period	January 1 2001 to December 31 2001
Lateral and surface forcing	NCEP-DOE reanalysis (Kanamitsu et al. 2002)
Horizontal resolution	27,750 m (=0.25°)
Long wave radiation	RRTMG Mlawer (1997)
Short wave radiation scheme	RRTMG Mlawer (1997) PBL Yonsei State Univ. (Hong et al. 2006)
Microphysics scheme	Morrison et al. (2005)
Shortwave radiation scheme	RRTMG Mlawer (1997)
Parameterizations for ensemble members	
Land surface schemes	NOAH (Mitchell and Jones 2005) SSIB (Xue et al. 1991)
	PLEIM-XIU (Pleim and Xiu 2003)
Cumulus parameterizations	Kain-Frisch (Kain 2004) Betts-Miller-Janjic (Janjic 1994)
	Grell-Devenyi (Grell and Devenyi 2002) Grell 3D ensembl (Grell 1993) Modified Tiedtke (Zhang et al. 2011)
	Simplified Arakawa-Schubert (Grell 1993)

3 Response of precipitation to land use change

3.1 Relationship to model climatology

The mean summer precipitation from the CTRL simulations corresponding to the mean of the ensemble members

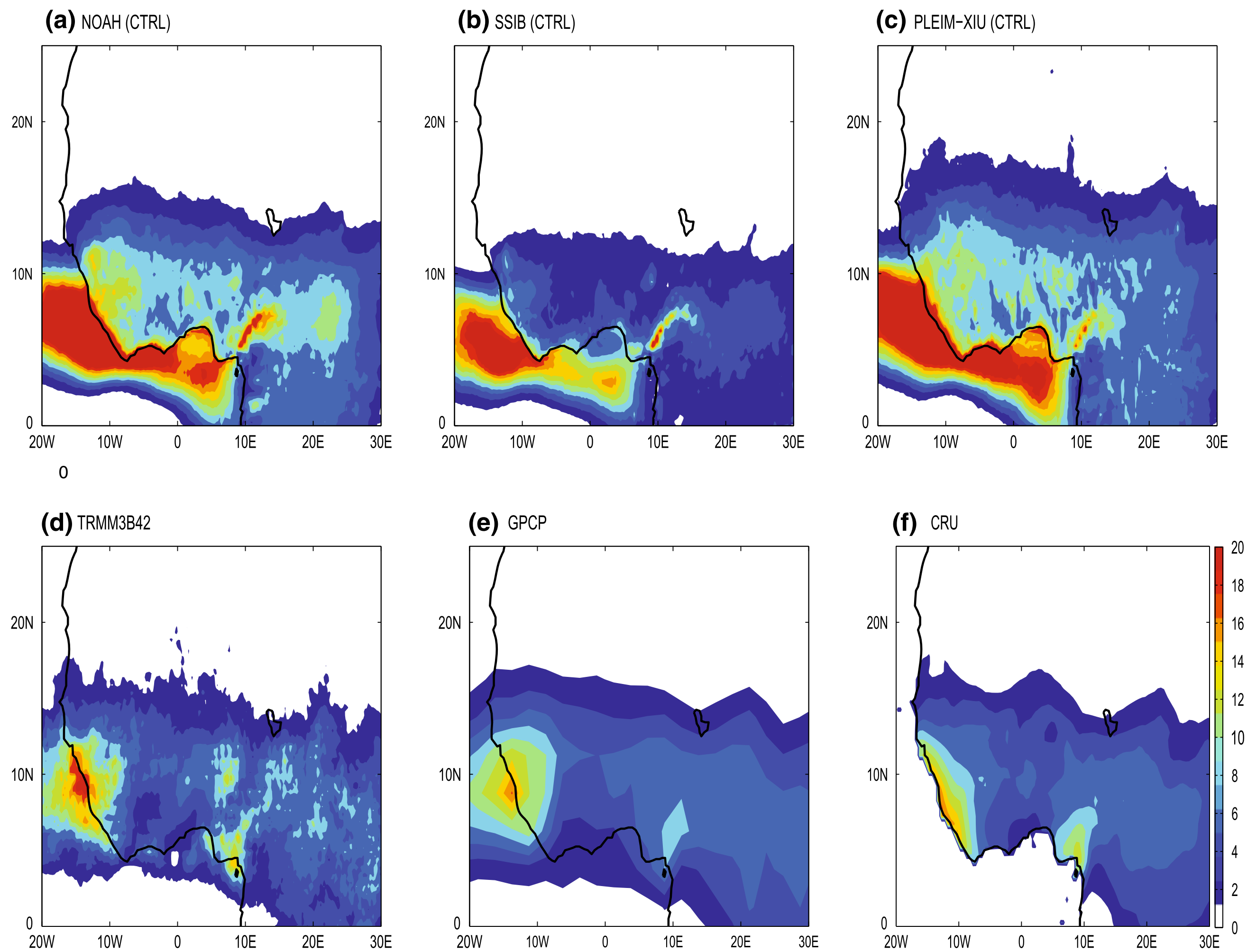

Fig. 3 Comparison of the ensemble means of the JJAS average precipitation (mm/day) from the CTRL simulations with observations

for each land surface scheme is evaluated against three observation datasets. These precipitation observations including the Tropical Rainfall Measuring Mission (TRMM3B42, Huffman et al. 2007), Global Precipitation Climatology Project (GPCP, Huffman et al. 2001) and University of East Angelia's Climate Research Unit TS 3.0 monthly precipitation data (Mitchell and Jones 2005) are shown in Fig. 3. The model simulations consistently differ from the observations over the Gulf of Guinea, with the model apparently overestimating precipitation although observations of precipitation over the ocean are entirely based on satellite retrievals, which is more uncertain compared to land-based observations. Over land, the simulations differ in their northward incursion of precipitation. For example the 2–4 mm/day precipitation band (dark blue shading) reaches Lake Chad in the case of NOAH LSM, a little to the south for SSIB and further north for PLEIM-XIU. In other words, on average, the SSIB simulations are relatively dry and the PLEIM-XIU experiments are relatively wet in comparison to NOAH. The implications of the model climatology to its response to land use change will be examined further.

The responses of mean summer model precipitation to the prescribed land use change are displayed in Fig. 4. Only differences that reached 95 % significance level between the CTRL and LULC simulations are shown. In Fig. 4a all ensemble members are included while in Fig. 4b, c and d the simulations are grouped by the specific land surface scheme used. As shown in Fig. 4a, small but statistically significant reduction in the mean summer precipitation is registered when all the simulations are considered together. But examining the results from the three land-surface schemes individually shows that the precipitation response is extremely sensitive to the land-surface schemes (Fig. 4a, b and c). The response is strongest for the ensemble members that used NOAH-LSM and relatively weaker for SSIB. There is virtually no response in the simulations with the PLEIM-XIU land surface scheme.

Given the large uncertainty in the response of mean summer precipitation to the prescribed land-use change, an

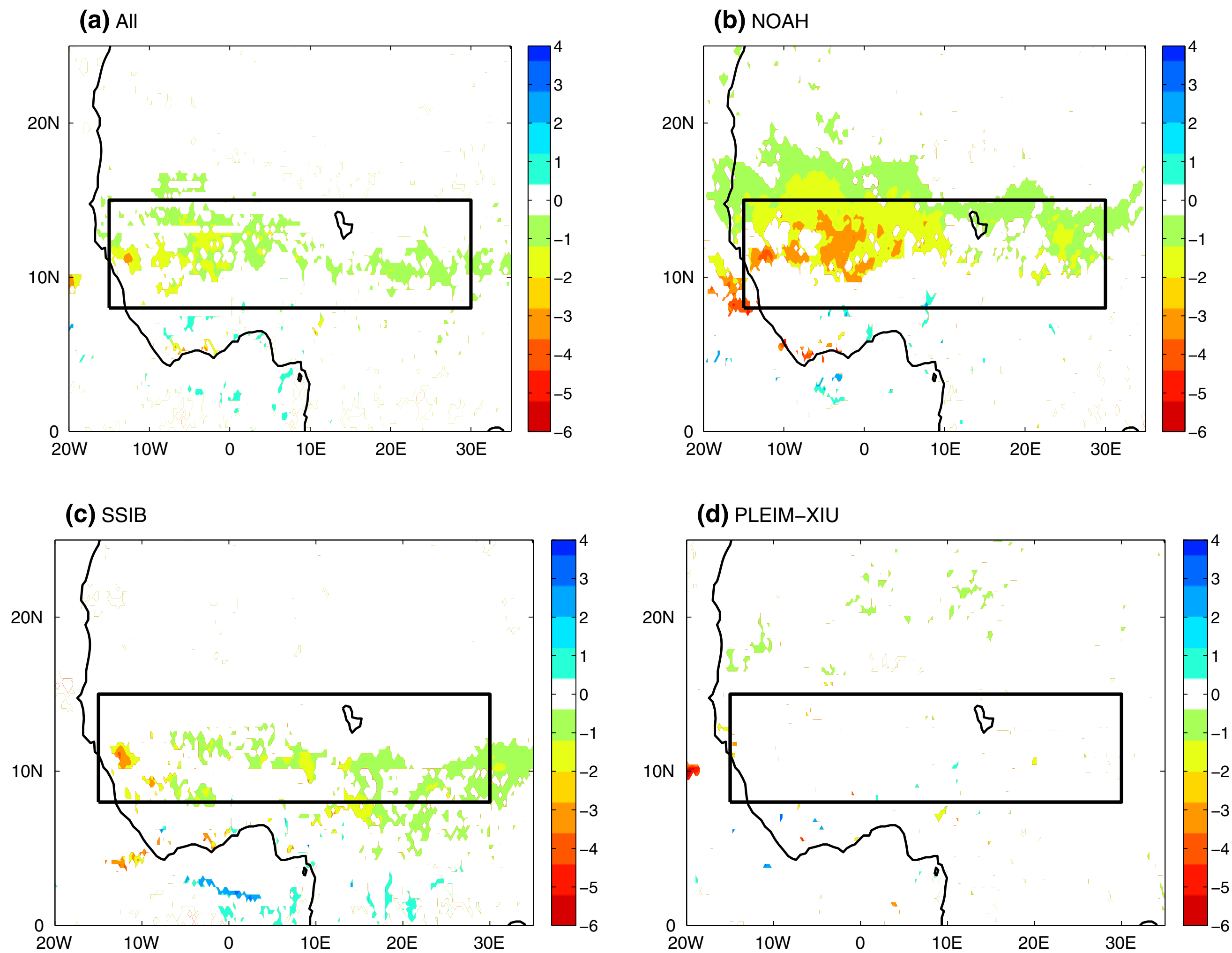

Fig. 4 Ensemble mean of JJAS average LULC minus CTRL precipitation in (mm/day). Only 95 % statistically significant differences are shown

important question is how this uncertainty compares with existing uncertainty in observations that could arise from measurement platform, sampling, etc. Figure 5 shows the change in precipitation associated with the prescribed land-use change against the mean precipitation from the corresponding CTRL simulations. The dashed lines correspond to precipitation from various observations. In addition to the TRMM, GPCP and CRU datasets mentioned earlier, the University of Delaware precipitation climatology is also included, all averaged over the box in Fig. 4. Even though the range of values of area mean precipitation from the model simulations is considerably wider than observations, the latter is not insignificant. Overall the precipitation response is weaker for simulations that are relatively dry or relatively wet, with the simulations that are in the middle range having stronger response in comparison. This is an interesting feature of the response that deserves further exploration.

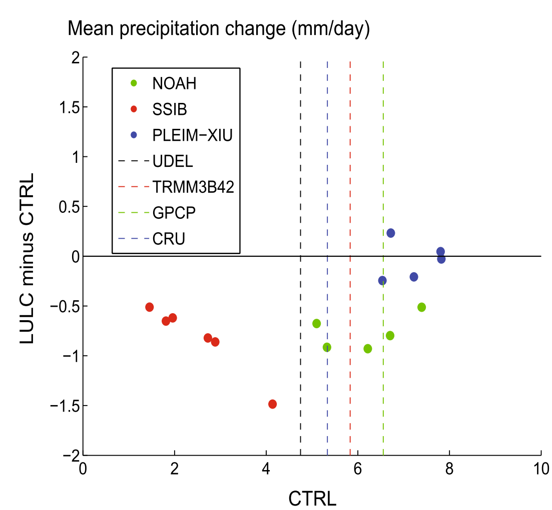

Fig. 5 The JJAS mean precipitation change versus the control values. The *dashed lines* represent those from observations. All are averaged over the *box* in Fig. 4

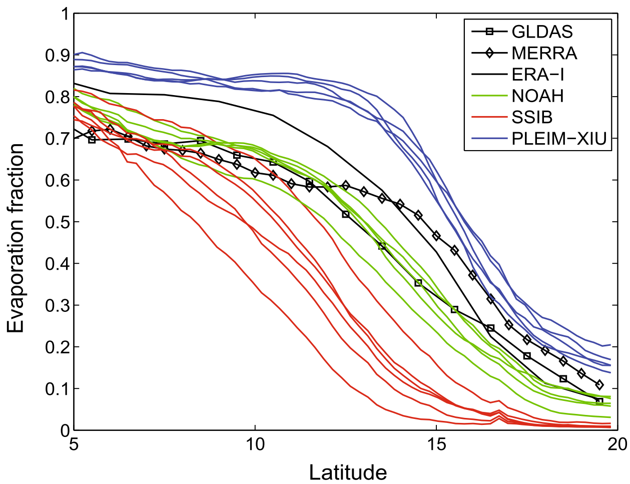

Fig. 6 Evaporation fraction averaged over the longitudinal extent of the *box* in Fig. 4

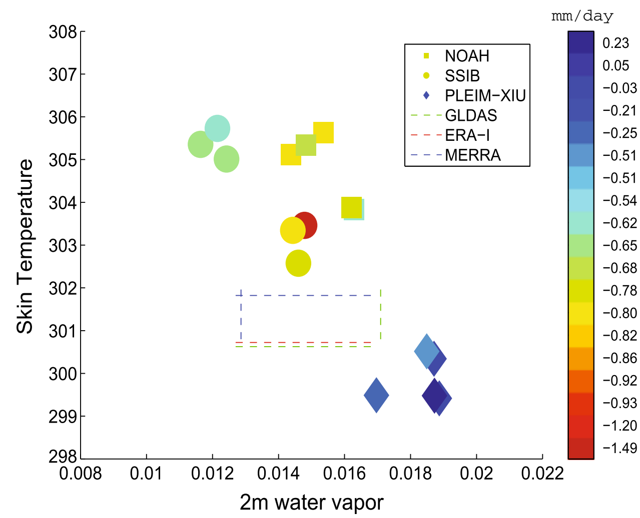

Fig. 7 The relationship between the change in precipitation due to LULC change to the 2 m vapor mixing ratio (kg/kg) of the corresponding CTRL simulation. All values are averaged over JJAS and the *box* on Fig. 4

Lying between the humid Equatorial Africa where ET is limited by the availability of energy and the arid Sahara Desert where ET is limited by the availability of soil moisture, the Sahel region is marked by a steep gradient of surface heat fluxes. Figure 6 shows the meridional structure of the zonally averaged evaporative fraction, which is defined as surface latent heat fluxes divided by the sum of the surface latent and sensible heating fluxes from the CTRL ensemble members as well as from three global reanalyses including ERA-Interim (Dee et al. 2011), Modern Era Retrospective Analysis For Research and Applications (MERRA, Rienecker et al. 2011), and Global Land Data Assimilation System (GLDAS V2, Rodell et al. 2004). The CTRL simulations that show relatively dry conditions of the Sahel (i.e., those using SSIB) tend to shift the steep gradient further to the south and those that are relatively wet (i.e., those using PLEIM-XIU) shift the gradient further north, while those using NOAH are in the middle. The better agreement of the simulations that used the NOAH scheme with GLDAS is not particularly surprising since NOAH is the primary model used in the data assimilation system and surface fluxes are model products with no observational constraint.

The meridional structure of the evaporative fraction of the CTRL simulations is particularly relevant to the response of the precipitation to land use change. If the land surface over the Sahel in a CTRL simulation were saturated, land use change would have little impact on the ET because ET can be maintained even with some reduction in soil moisture caused by land use change (the PLEIM-XIU case). On the other hand, if the Sahel were dry in the CTRL simulation, land use change would also have less effect because moisture cannot be significantly further reduced to affect the fluxes (the SSIB case). Therefore the maximum sensitivity is realized in the CTRL simulations lying between the two extremes (the NOAH case), in which the sensitivity of surface fluxes to changes in soil moisture is high. This is further demonstrated by the mean near surface (2 m) temperature and specific humidity fields of the CTRL simulations and their correlations with precipitation changes using the three land surface schemes (Fig. 7). Once again, in comparison to the reanalyses, which are marked by values within the dashed box as a reference, the boundary layer from the SSIB CTRL simulations is relatively warmer and dryer, while that from PLEIM-XIU is wetter and cooler. The CTRL simulations using NOAH are in between but warmer than the reanalyses. The main point here is that models with wet or dry biases are likely to underestimate the response to land use change so accurate representation of the spatial (especially meridional) distribution of surface fluxes is necessary for a model to have a credible response to these changes.

3.2 Mechanism of the response

In the last sub-section, it was shown that the prescribed land-surface degradation results in a wide-range of responses in mean summer precipitation over the Sahel, with associated spread in surface temperature and evaporative fraction. In this sub-section, the physical processes that link land surface processes with precipitation and uncertainties that lead to this wide range of responses are discussed. From the perspective of atmospheric moisture balance, the reduction in precipitation is a result of changes in local surface ET and atmospheric moisture convergence.

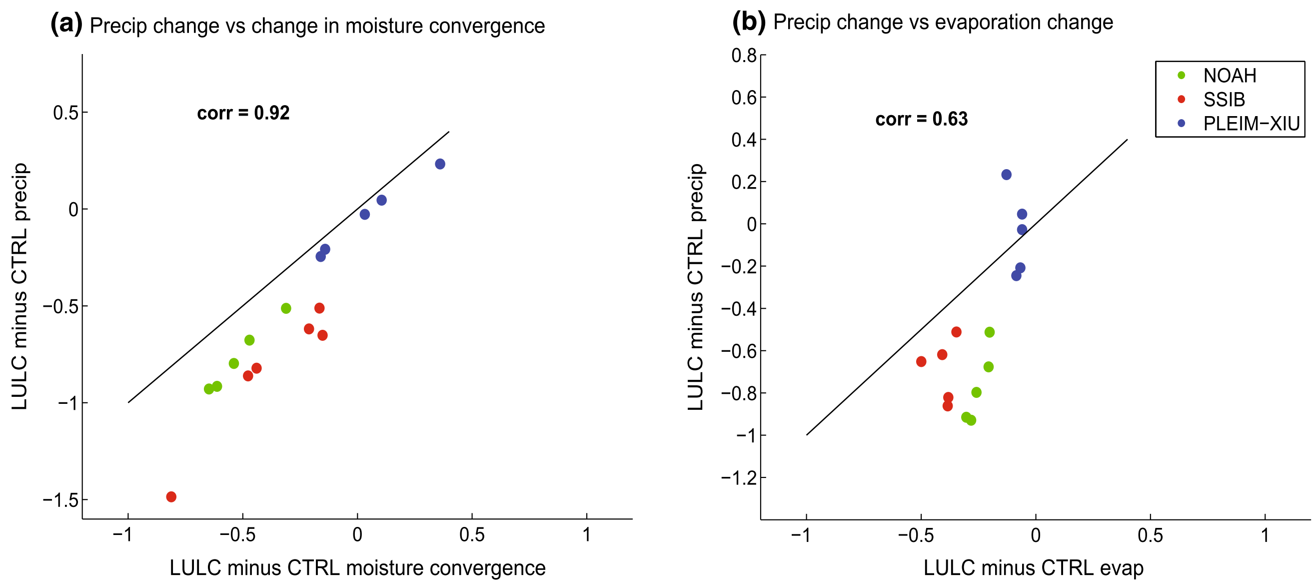

FIG. 8 The relationship between the change in precipitation due to LULC change to the corre- sponding change in evaporation. Both are in mm/day

Therefore assessing the contributions of these two components to the total moisture budget is a natural starting point. Figure 8a shows the relationship between precipitation change and the change in the vertically integrated moisture convergence and Fig. 8b shows the former with the change in ET. The points on Fig. 8a and b would fall on the solid lines if all the precipitation change is explained by changes in moisture convergence or evaporation respectively. While precipitation is sensitive to both changes in moisture convergence and local ET, it correlates more strongly with the former (0.92 vs 0.63). Thus land degradation affects the availability of moisture not only through the change in ET, but more importantly, through changes in circulation and moisture transport. A study using the AMMA Land Surface Model Intercomparison Project (ALMIP, Boone et al. 2009) data indicated that the ratio of evaporation over precipitation in the West African monsoon area is about 52 % (Xue et al. 2010). Another West African climate study with one GCM (Xue 1997) showed that evaporation change accounts for about 53 % of precipitation change after the LULC was changed. That multi-model study revealed that large scale moisture convergence plays a more important role in producing the precipitation change and discrepancies among land schemes in responding to the LULC change.

In order to understand how land use change affects circulation, we first consider the primary mechanism of moisture transport for the African Monsoon. The African monsoon circulation is forced by the Sahara heat low (Xue et al. 2010) and the associated mid-tropospheric high. The former drives cyclonic, near surface moist southwesterly winds from the Gulf of Guinea and the high associated with this heat low in turn drives mid-tropospheric anticyclonic circulation (African Easterly Jet) that transports moisture westward out of the Sahel region into the Atlantic (Hagos and Cook 2008; Hagos and Zhang 2010). This meridional temperature gradient along with the dry Harmattan winds from the northeast determine how far north the moisture is transported by the low-level southwesterly winds, the latitudinal location of the African Easterly Jet (AEJ), and ultimately the Sahel precipitation. Figure 9 shows the profiles of mean zonal wind and specific humidity from the CTRL simulations and from the ERA-Interim reanalysis. The African Easterly Jet position for the simulations with the NOAH land surface scheme is in best agreement with that of ERA-Interim, while it is too far south for SSIB and too far north for PLEIM-XIU. Furthermore in the case of the PLEIM-XIU land surface scheme, there is a larger moisture excursion into the continent compared to the other simulations as well as the ERA-Interim reanalysis.

Having observed the differences in the latitudinal location of the AEJ among the three sets of simulations, the next question is how does AEJ respond to land use change? Figure 10 shows the water vapor mixing ratio from the LULC experiments and the change in zonal wind due to land use change. In both NOAH and SSIB, the land use degradation enhances the AEJ, but the latitudinal location of the peak change differs between the simulations (about 8°N for NOAH and 5°N for SSIB). This partly follows from the latitudinal locations of the AEJ in the corresponding CTRL simulations which peak at about 12°N and 9°N for the two surface schemes respectively (Fig. 9). The

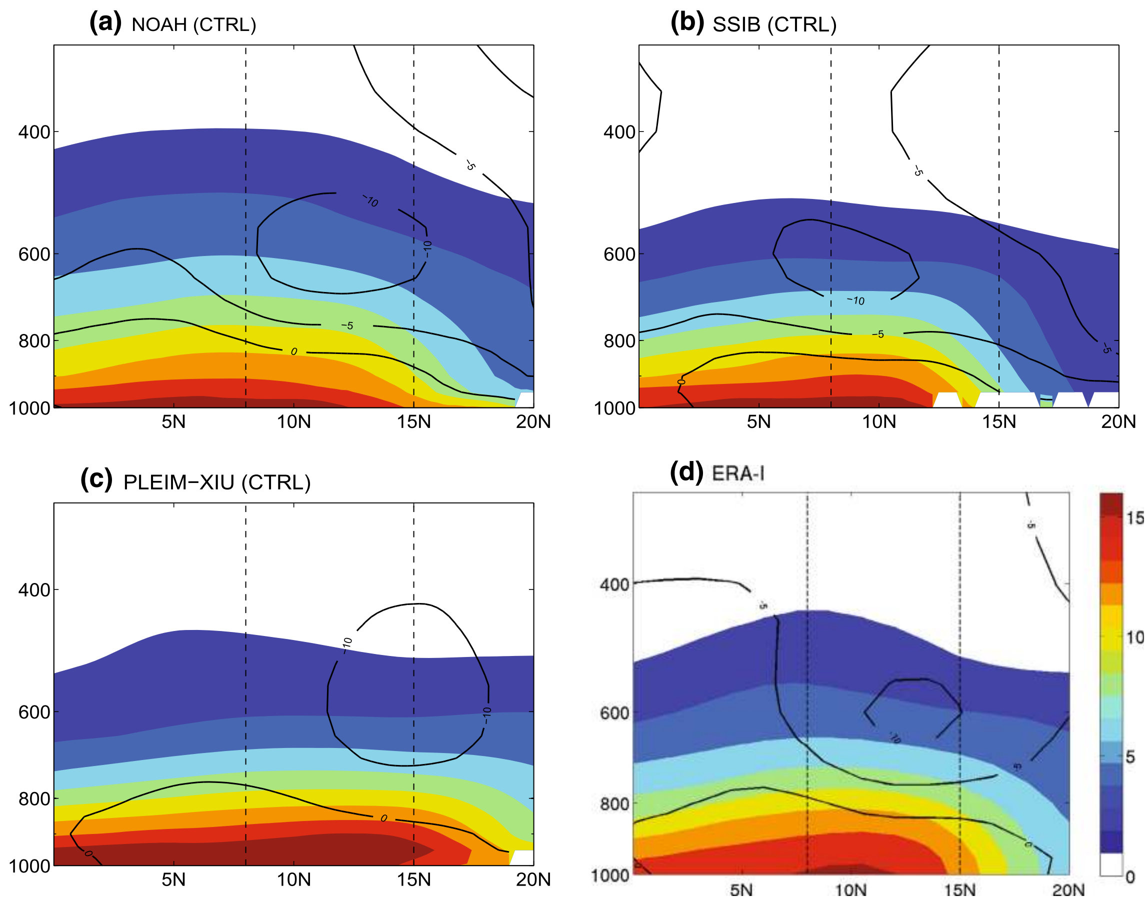

Fig. 9 JJAS mean zonal mean wind (m/s) and water vapor mixing ratio (g/kg) from the control simulations and ERA-interim reanalysis

response of the AEJ to land use change in PLEIM-XIU is very weak (Fig. 10b). The moisture distribution in LULC is very similar to those of the CTRL case. So even if one assumes the moisture distribution under LULC remains the same, the accelerated AEJ under the degraded land use would drive more moisture out of the Sahel, thereby reducing the precipitation. In all the simulations, the low-level westerly flow, which has a climatological peak near 900 hPa at about 8°N (Pu and Cook 2012), is not significantly affected by the land use change possibly because it is farther south from the region where the land use change is prescribed.

Finally as a thermal wind, the AEJ is related to the meridional temperature gradients. Thus changes in temperature distribution associated with land use change deserve a look. Figure 11 shows the means of the differences in skin temperature between the LULC ensemble members and their corresponding CTRL simulations. In general, the prescribed land use change introduces temperature changes of about 0.5 K, but the spatial distributions vary. For the SSIB cases, the peaks of surface warming are located between 10°N and 12°N, while those of the NOAH cases are between 12°N and 15°N. This partly explains the difference in the latitudinal location of the peak change in the AEJ (Fig. 10). The peak changes in surface temperature for the PLEIM-XIU cases peak between 12°N and 17°N and are generally about half of the SSIB cases in magnitude.

4 Discussion

This study examines the uncertainties in model response of the West African Monsoon to changes in land use that are estimated to have occurred over the last 60 years in the African Sahel using two groups of ensemble regional model simulations. In the control (CTRL) simulations, potential vegetation is prescribed, while in the land use change (LULC) simulations, the estimated land degradation associated with the observed increase in crop and pasture land is prescribed. For each case, sixteen simulations that correspond to combinations of six cumulus parameterizations and three land surface schemes are performed (two simulations with unrealistic climatology are

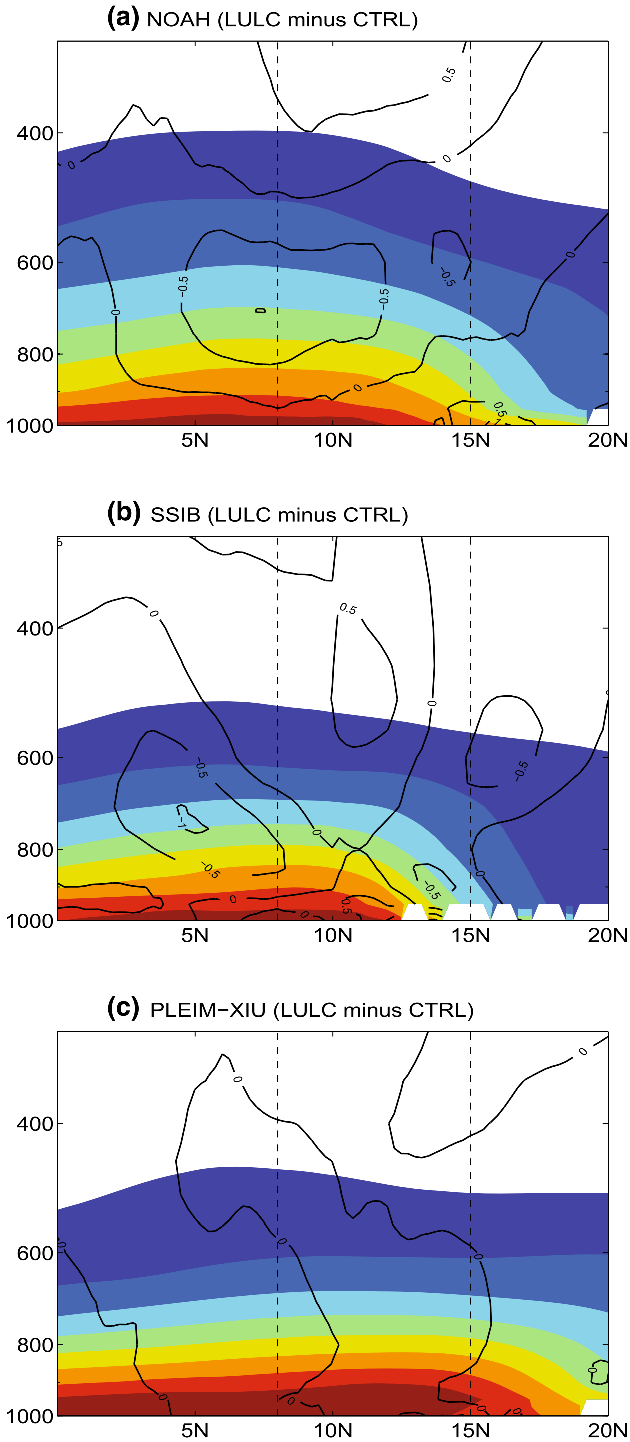

Fig. 10 The change in JJAS mean zonal wind due to the LULC change (*contours*, m/s) and the LULC water vapor mixing ratio (*shaded*, g/kg)

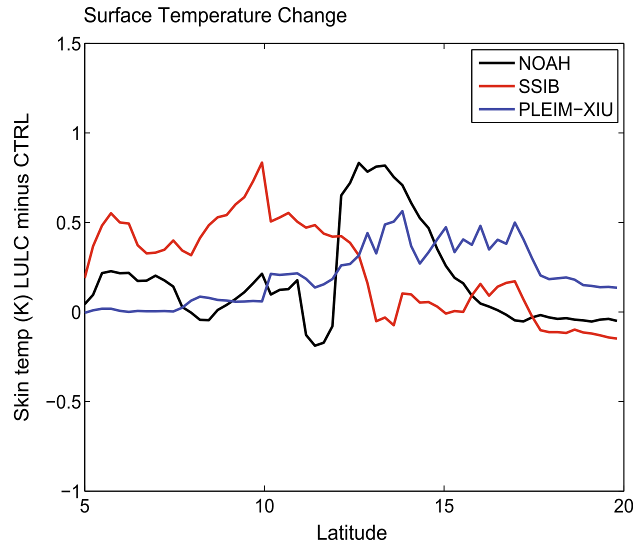

Fig. 11 Ensemble means of the change in surface temperature (K) due to LULC change

discarded). All simulations have the same prescribed changes in surface albedo, green fraction and emissivity. Observations of precipitation and reanalysis of wind, water vapor mixing ratio, surface fluxes are used to evaluate the ensemble members and provide the constraints for a realistic estimate of the impact of land-surface degradation on Sahel precipitation.

In general, land surface degradation reduces surface evaporation in favor of surface sensible heating and increases surface temperature. The resulting increase in meridional surface temperature gradient across the Sahel (Fig. 11) enhances the AEJ (Fig. 10), which transports more moisture out of the Sahel region and reduces precipitation (Fig. 4). This is in agreement with the findings of Abiodun et al. (2008). The contribution of reduced ET to the change in precipitation is comparable to that by the change in circulation. The results are consistent among ensemble members with different cumulus parameterizations, but are very sensitive to the land surface scheme used. Two mechanisms play a role in this model sensitivity. First, different land surface schemes simulate different ET response to land use change. This leads to differences in the precipitation response through differences in local precipitation recycling. Second, land surface schemes determine the meridional structure of the evaporative fraction (or equivalently Bowen ratio, the partitioning of surface fluxes between latent and sensible heat fluxes), which shows a steep meridional gradient across the Sahel (Fig. 6). This modulates the meridional location of the model peak temperature response, leading to differences in the response of the model AEJ and precipitation.

Our finding is similar to those of the Global Land–Atmosphere Coupling Experiment (Guo and et al. 2006), where comparison of various combinations of atmospheric and land models revealed that the much of the differences in precipitation can be explained by the sensitivity of evaporation and hence surface temperature to soil moisture in the land models and the direct sensitivity of precipitation to evaporation through local precipitation recycling plays a smaller role in the inter-model difference. In this context, much of the uncertainty in the model response lies in the meridional structure of evaporation/temperature and how it responds to changes in soil moisture. As suggested by Guo et al. 2006, details of the land model scheme, particularly those associated with transpiration, bare soil evaporation and canopy interception loss, likely explain this uncertainty. Consistent with this, the response of the atmosphere to the changes in evaporation (modification to surface temperature, changes in AEJ and moisture transport and precipitation) is fairly consistent among the cumulus schemes used. Therefore accurate depiction of the impact of land use change on monsoon precipitation depends on representation of land surface processes and surface fluxes by the models. To this end, accurate in situ or remotely-sensed measurements of surface fields over the broad latitudinal cross section of the Sahel might be necessary to provide constraints on land surface parameterizations to realistically simulate the response to land use change.

This study does not explore the full range of uncertainty in how the Sahel climate responds to LULC. Rather we address specifically uncertainty in LULC response due to parameterization uncertainty and elucidate the physical and dynamical mechanisms for how sensitivity to parameterizations translates to uncertainty in LULC response. The latter improves understanding of how LULC influences the Sahel precipitation, and similar mechanisms should apply whether the uncertainty arises due to parameterizations, LULC scenarios, or soil moisture initialization. Providing a comprehensive assessment of uncertainty in model response and how uncertainty from each factor compares are beyond the scope of this study. Land degradation in the African Sahel has also resulted in soil texture change. Feddema (1998) has shown that variations in soil water holding capacity associated with land degradation can have important effects on evapotranspiration and local water balances. The relative contributions of LULC change and soil texture change and the degree to which uncertainty in model response to these change feeds back to the monsoon dynamics is a subject of future study.

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