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Key Points:
- Feedbacks on projected Sahel rainfall from long-term soil moisture changes significantly impact precipitation projections in climate models
- Feedbacks on climate model projections of Sahel rainfall from long-term soil moisture changes vary in sign across models
- These results call for further assessment and evaluation of soil moisture-atmosphere interactions across current-generation climate models

Correspondence to:
A. Berg,
ab5@princeton.edu

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Uncertain soil moisture feedbacks in model projections of Sahel precipitation

Alexis Berg[1], Benjamin R. Lintner[2], Kirsten Findell[3], and Alessandra Giannini[4]

[1]Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey, USA, [2]Department of Environmental Sciences, State University of New Jersey, Rutgers, New Brunswick, New Jersey, USA, [3]NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey, USA, [4]International Research for Climate and Society (IRI), Earth Institute, Columbia University, Palisades, New York, USA

Abstract Given the uncertainties in climate model projections of Sahel precipitation, at the northern edge of the West African Monsoon, understanding the factors governing projected precipitation changes in this semiarid region is crucial. This study investigates how long-term soil moisture changes projected under climate change may feedback on projected changes of Sahel rainfall, using simulations with and without soil moisture change from five climate models participating in the Global Land Atmosphere Coupling Experiment-Coupled Model Intercomparison Project phase 5 experiment. In four out of five models analyzed, soil moisture feedbacks significantly influence the projected West African precipitation response to warming; however, the sign of these feedbacks differs across the models. These results demonstrate that reducing uncertainties across model projections of the West African Monsoon requires, among other factors, improved mechanistic understanding and constraint of simulated land-atmosphere feedbacks, even at the large spatial scales considered here.

Plain Language Summary Climate model projections of Sahel rainfall remain notoriously uncertain; understanding the physical processes responsible for this uncertainty is thus crucial. Our study focuses on analyzing the feedbacks of soil moisture changes on model projections of the West African Monsoon under global warming. Soil moisture-atmosphere interactions have been shown in prior studies to play an important role in this region, but the potential feedbacks of long-term soil moisture changes on projected precipitation changes have not been investigated specifically. To isolate these feedbacks, we use targeted simulations from five climate models, with and without soil moisture change. Importantly, we find that climate models exhibit soil moisture-precipitation feedbacks of different sign in this region: in some models soil moisture changes amplify precipitation changes (positive feedback), in others they dampen them (negative feedback). The impact of those feedbacks is in some cases of comparable amplitude to the projected precipitation changes themselves. In other words, we show, over a subset of climate models, how land-atmosphere interactions may be a cause of uncertainty in model projections of precipitation; we emphasize the need to evaluate these processes carefully in current and next-generation climate model simulations.

1. Introduction

West Africa is a densely populated and cultivated area. Irrigation is largely absent, and smallholder family farming depends on seasonal rainfall from the West African Monsoon (WAM), especially in the drier, northernmost Sahel region. The dire impacts on local populations of past variations in WAM rainfall, such as the multidecadal drought of the 1970s and 1980s, underscore their vulnerability to potential adverse future changes in the WAM under global warming. It is thus crucial to provide robust projections of such changes to inform planning and adaptation.

Because land warms faster than oceans, global warming may reinforce the land-sea contrast and associated low-level pressure gradients and monsoonal winds; some climate model studies suggest such an evolution [*Haarsma et al.*, 2005]. The direct impact on land of greenhouse gas forcing could also enhance WAM precipitation locally [*Giannini*, 2010; *Dong and Sutton*, 2015]. On the other hand, observational and model studies suggest that global ocean warming by itself would diminish Sahelian rainfall [*Held et al.*, 2005; *Hagos and Cook*, 2008; *Ting et al.*, 2009; *Fasullo*, 2012]. Overall, consensus among model projections of WAM precipitation under global warming is weak, with current-generation climate models projecting both drying and wetting [*Cook*, 2008; *Biasutti*, 2013; *Park et al.*, 2015]. Reducing this uncertainty requires knowledge of the physical factors underlying model projections and how these are represented in models.

Historical decadal variations of the WAM have been shown to be governed, to leading order, by variations in patterns of sea surface temperatures (SSTs) (see *Rodríguez-Fonseca et al.* [2015] for a review). Climate models forced by observed SST anomalies reproduce, at least qualitatively, observed variations in the WAM [e.g., *Biasutti*, 2013]. Thus, differences in model projections of SST patterns have been investigated as the proximate cause of intermodel spread in projected WAM changes with global warming [*Biasutti et al.*, 2008; *Giannini et al.*, 2013; *Park et al.*, 2015]. Such studies reveal that up to 50% of the variance in model projections of Sahel rainfall may be explained by differences in projected global and regional SSTs [*Giannini et al.*, 2013; *Park et al.*, 2015]. Still, while intermodel differences in projected SSTs may provide a leading-order explanation of model uncertainties, physical processes unrelated to SST patterns may contribute to the large spread in the response of WAM precipitation to warming across climate models.

We focus here on understanding how projected soil moisture changes may feedback on projected WAM precipitation in climate models. A large body of work highlights the importance of coupled land-atmosphere processes in West African climate variability over a range of temporal and spatial scales [e.g., *Xue et al.*, 2012]. Soil moisture-atmosphere interactions, in particular, have been shown to affect precipitation variability from seasonal to decadal timescales [*Zeng et al.*, 1999; *Giannini et al.*, 2003; *Koster et al.*, 2004]. More recently, results from the Global Land Atmosphere Coupling Experiment-Coupled Model Intercomparison Project phase 5 (GLACE-CMIP5) experiment have shown that at continental to global scales, changes in soil moisture induced by climate change can feedback on surface climate, including precipitation [*Seneviratne et al.*, 2013; *Lorenz et al.*, 2016; *May et al.*, 2015; *Berg et al.*, 2016a]. In a previous study using the GLACE-CMIP5 ensemble [*Berg et al.*, 2016b], we showed that in present-day climate, soil moisture-atmosphere interactions demonstrably impact the mean seasonality and strength of the WAM. Here our focus turns to the potential effects of longer-term changes in mean soil moisture values as the climate warms: that is, to what extent do soil moisture changes projected by climate change simulations feedback on simulated precipitation changes over the Sahel? To answer this question, we compare climate projections over West Africa in the GLACE-CMIP5 simulations. Data and methods are described in section 2. Results are presented in section 3 and discussed in section 4.

2. Data and Methods

We analyze simulations with models participating in the GLACE-CMIP5 experiment. All simulations are land-atmosphere transient climate change simulations extending over 1950–2100, with transient sea surface temperatures (SSTs), sea ice and radiative forcing agent concentrations prescribed from the corresponding CMIP5 simulations using the historical simulations over 1950–2005, and the representative concentration pathway 8.5 (RCP8.5) scenario thereafter. In simulation SM_FIX, total soil moisture is overridden in the respective models, pixel by pixel, by the climatological seasonal cycle of soil moisture over 1971–2000 from the corresponding historical, fully coupled CMIP5 simulation; i.e., the 30 year climatological seasonal cycle is repeated yearly throughout the simulation. There is thus no long-term change in soil moisture in SM_FIX in response to anthropogenic forcing. Another simulation, SM_TRND, is performed, identical to SM_FIX except that a centered, 30 year moving average transient climatology of soil moisture (from the historical and then RCP8.5 coupled simulation) is used to prescribe soil moisture. Over the first and last 15 years, the climatologies of 1950–1979 and 2071–2100, respectively, are prescribed. Simulation SM_TRND thus includes long-term soil moisture changes induced by anthropogenic forcing. In both SM_FIX and SM_TRND soil moisture is prescribed at every level in the soil column; depending on the model, soil moisture is prescribed at every time step, daily, or monthly with interpolation applied as necessary. Finally, a third simulation, SM_INT, is performed, with the same boundary conditions as SM_FIX and SM_TRND, but with interactive soil moisture. SM_INT serves as a control simulation (instead of the parent coupled CMIP5 simulations) as it shares the Atmospheric Model Intercomparison Project-like configuration of the other two runs.

Six modeling centers participated in GLACE-CMIP5, though we analyze simulations from only five models: the Geophysical Fluid Dynamic Laboratory (GFDL) Earth System Model with the Modular Ocean Model (GFDL-ESM2M, hereinafter ESM2M); the European Consortium Earth System Model (EC-EARTH) developed by a consortium of European research institutions (see www.to.isac.cnr.it/ecearth/); the Max Planck Institute (MPI) for Meteorology Earth System Model (MPI-ESM); the National Center for Atmospheric Research (NCAR) Community Climate System Model, version 4 (CCSM4); and the Institut Pierre-Simon Laplace Coupled Model, version 5A (IPSL-CM5A). The reader is referred to *Seneviratne et al.* [2013] for further discussion of the models and the experimental protocol of GLACE-CMIP5. We do not consider simulations from the Australian Community Climate and Earth System Simulator (ACCESS) model because of issues in the seasonality of the prescribed soil moisture in SM_FIX in this model, which strongly impact the WAM projection. Note that CCSM4 did not perform simulation SM_INT, so the coupled CMIP5 simulation is used as the control instead; since our results emphasize comparisons between SM_TRND and SM_FIX, this does not affect our conclusions.

In this study, we focus on the feedback of long-term soil moisture changes on projected changes in Sahel precipitation. Denoting as Δ the change in precipitation between 30 year present (1971–2000) and future (2056–2085) in each run, we consider the difference: ΔSM_TRND – ΔSM_FIX, corresponding to the effect of mean soil moisture change on simulated precipitation change. Note that since both SM_TRND and SM_FIX include prescribed soil moisture, differences in WAM precipitation between these simulations only stem from differences in mean soil moisture levels.

As in *Lorenz et al.* [2016], because of the missing trend over the last 15 years of SM_TRND related to the unavailability of data for the 30 year running mean, we only analyze model output through 2085. The latter time period differs from the 2071–2100 period considered in either *Seneviratne et al.* [2013] or *Berg et al.* [2016a]. Focusing on 2056–2085 allows a more rigorous comparison between the simulations, which may be all the more important at the regional scale. However, selecting different ending periods does not qualitatively affect our results. Finally, our analysis focuses on June-July-August-September (JJAS) climate, as this is the period during which most WAM precipitation occurs.

3. Results

3.1. Regional Precipitation Changes and Associated Soil Moisture Changes

Figure 1a illustrates the climatological, present-day WAM in the GLACE-CMIP5 models in the control, interactive-soil-moisture case (SM_INT), and the associated projected precipitation changes in the future. As shown in *Berg et al.* [2016b], the GLACE-CMIP5 models exhibit a range of behaviors in their depiction of the WAM (see climatological isohyets in Figure 1a; the reader is also referred to Figure 2 in *Berg et al.* [2016b]). For example, ESM2M produces a strong monsoon, with rainfall advancing far to the north over the continent (e.g., the 1 mm/d isohyet lies north of 20°N), while IPSL-CM5A produces a much weaker monsoon, with precipitation remaining too close to the Guinean Gulf coast. The location of the poleward margin of the WAM, defined here as the band between 1 and 5 mm/d of climatological rainfall (roughly equivalent to the conventional isohyet-based definition of the Sahel domain, i.e., from 100 mm to 600 mm of seasonal rainfall accumulation), varies greatly across these models. In other words, the simulated Sahel occurs at different latitudes across the suite of GLACE-CMIP5 models.

Consistent with uncertainties in the broader CMIP5 ensemble [e.g., *Biasutti*, 2013], projected future rainfall changes over West Africa also vary across GLACE-CMIP5. While there is a general tendency for increased precipitation over, or along the coast of, the Gulf of Guinea (except in CCSM4), projected changes farther inland indicate some spread across models. Over the poleward margin of the monsoon, EC-EARTH shows no consistent changes in precipitation, and MPI-ESM shows a significant change only in the small region of rainfall reduction in the westernmost portion of the model's simulated Sahel. IPSL-CM5A simulates a decrease in precipitation over most of southern West Africa, although this decrease barely extends into the Sahel in that model. ESM2M projects a clear reduction in precipitation over most of the Sahel, with a most pronounced decline in the eastern half, which is consistent with previous analyses of GFDL models sharing the same atmospheric component and reflects a strong drying response to mean ocean warming in this model [e.g., *Held et al.*, 2005]. In contrast, CCSM4 simulates a significant and widespread increase in precipitation, except over the westernmost part of the domain. As can be expected given the experimental configuration, i.e., the same oceanic boundary conditions and radiative forcing, these different trends are consistent with the projected changes in the corresponding RCP8.5 CMIP5 simulations from the same models [e.g., *Biasutti*, 2013, Figure 3b].

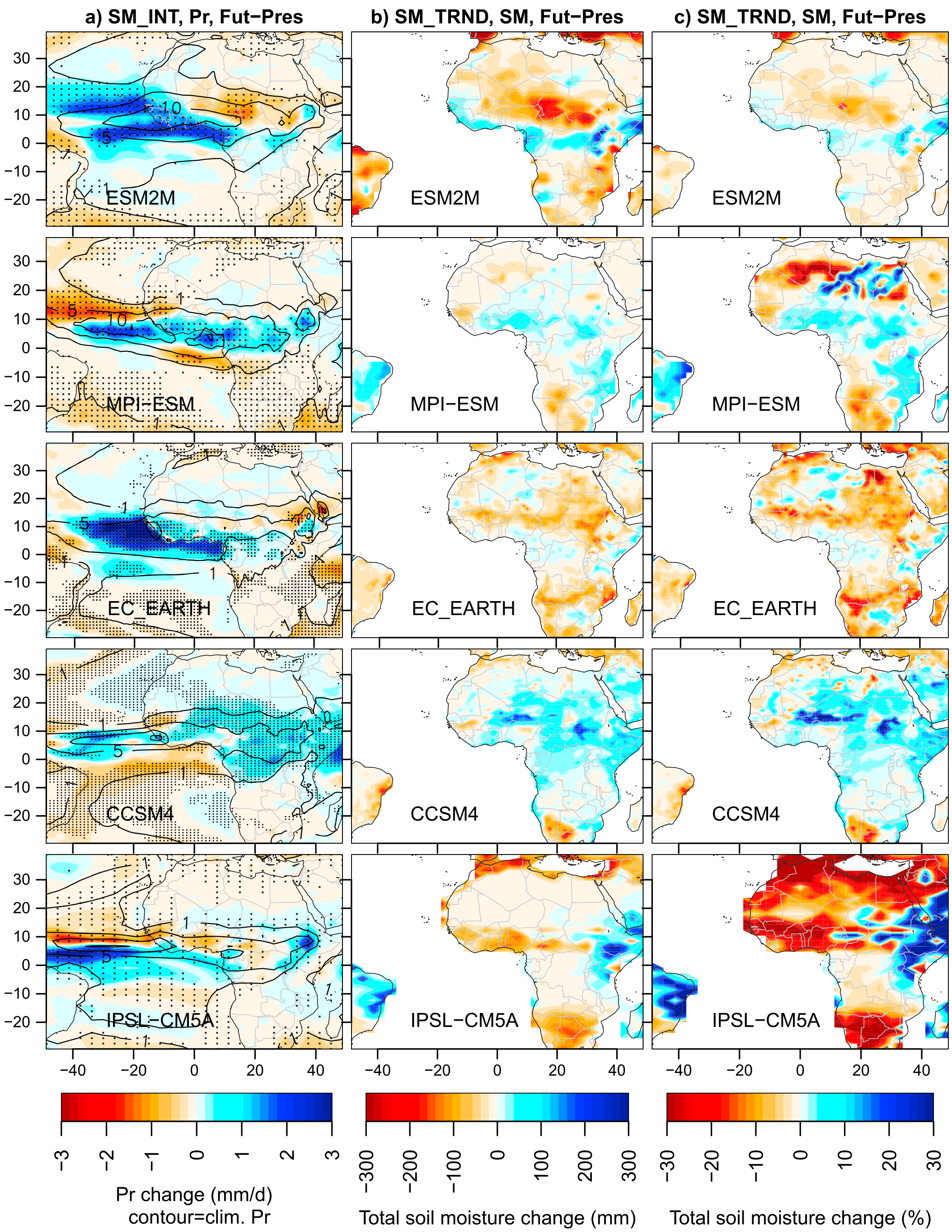

Figure 1. (a) June–September (JJAS) precipitation change in SM_INT between 1971–2000 and 2056–2085 (mm/d; shading) in the five models (rows) and present-day climatology in the same simulation (contour lines at 1, 5, and 10 mm/d). Stippling indicates significant differences (at 5%) according to simple *t* test. (b) Prescribed JJAS total soil moisture changes in SM_TRND between 1971–2000 and 2056–2085, in millimeters; (c) same as Figure 1b, in percentage of present-day mean JJAS value. For readability, colors saturate beyond ±3 mm/d in Figure 1a, beyond ±300 mm in Figure 1b, and ±30% in Figure 1c.

Figure 1b shows trends in total soil moisture from the CMIP5 projections that are prescribed in simulation SM_TRND over West Africa. Because total soil depth varies between models, total soil moisture levels differ; thus, in addition to changes in absolute soil moisture values (mm; Figure 1b), Figure 1c also shows relative changes (in percent of present-day mean values). For instance, although equivalent in absolute magnitude to other models, simulated soil moisture changes in IPSL-CM5A are larger in relative terms, as the soil is more shallow (2 m) and mean present-day soil moisture lower in that model. Overall, long-term changes in soil moisture are broadly consistent with simulated changes in precipitation (Figure 1a) from SM_INT in each model. Three models (ESM2M, EC-EARTH, and IPSL-CM5A) project negative soil moisture anomalies at the poleward edge of the WAM. One model (CCSM4) projects a clear soil wetting. In MPI-ESM, increasing soil moisture occurs over most of the monsoon domain except in the west; however, this signal becomes weaker toward the northern part of the monsoon. In EC-EARTH, the zonal band of projected soil moisture decrease around 10–15°N is not clearly associated with local changes in precipitation (Figure 1a); rather, it reflects an increase in evapotranspiration (ET) over that region (not shown).

3.2. Feedback of Soil Moisture Changes on Regional Precipitation Changes

Figure 2 shows projected JJAS precipitation changes in SM_FIX and SM_TRND, and the effect of the change in soil moisture, which is given by the difference between the two runs (Figure 2c). Note that projections from SM_TRND are broadly consistent with projections from the control case SM_INT (Figure 1a). The spatial patterns of precipitation change in SM_TRND and SM_FIX also bear a strong resemblance to one another, indicating that feedbacks from soil moisture change do not fundamentally alter the large-scale spatial patterns of change projected by the different models. Nevertheless, Figure 2c reveals significant impacts of soil moisture changes on precipitation projections.

In ESM2M and IPSL-CM5A, the prescribed decrease in soil moisture leads to a significant reduction in precipitation, including over the poleward margin of the monsoon. These models thus display a positive or amplifying soil moisture-precipitation feedback. The decrease in precipitation caused by progressive loss of soil moisture over the 21st century is of the same order of magnitude (~1 mm/d) as the projected precipitation changes in SM_FIX. Furthermore, over most of West Africa in IPSL-CM5A, and over the central part of the Sudano-Sahelian domain in ESM2M (around 0°E), the decrease in precipitation in SM_TRND appears mostly due to the prescribed decrease in soil moisture, as little precipitation decrease is apparent in SM_FIX.

By contrast, in CCSM4 and EC-EARTH, the feedback on projected precipitation from soil moisture changes is negative. In CCSM4, the prescribed increase in soil moisture leads to reduced precipitation over most of the poleward margin of the monsoon (conversely, the prescribed decrease in soil moisture over the westernmost part of the Sahel leads to increased precipitation); in EC-EARTH, the prescribed decrease in soil moisture leads to a slight increase in precipitation over the same region. In CCSM4, the decrease in precipitation caused by soil moisture changes is, again, of similar magnitude in absolute terms (~1 mm/d)—but of opposite sign—compared to the projected increase in precipitation that happens in the absence of soil moisture changes in SM_FIX. In EC-EARTH, the slight increase in precipitation caused by soil moisture decrease over the poleward margin of the monsoon is also large enough to offset the precipitation increase that happens in the absence of soil moisture changes in SM_FIX.

Finally, in MPI-ESM, differences in projected precipitation between SM_TRND and SM_FIX are more muted and mostly restricted to the southern part of West Africa. A negative but weak precipitation response over that region is evident but is associated with prescribed soil moisture changes of both signs, so that a coherent soil moisture-precipitation feedback is difficult to identify. The weaker response to soil moisture changes in MPI-ESM is consistent with previous analyses demonstrating the weakest influence of soil moisture on surface climate in this model compared to the other GLACE-CMIP5 models, over the WAM region [*Berg et al.*, 2016b] and globally [*Orth and Seneviratne*, 2017]—see also section 3.3 below.

Overall, our results indicate that the feedback of mean soil moisture change on future Sahel precipitation varies in sign across models, with two models displaying positive (amplifying) feedbacks, two models displaying negative (damping) feedbacks, and one model showing no clear feedback.

3.3. Physical Interpretation of Different Soil Moisture-Precipitation Feedbacks

A comprehensive, 3-D set of atmospheric variables is unavailable in the GLACE-CMIP5 experiment to perform a detailed analysis of the different dynamic and thermodynamic processes associated with the simulated precipitation responses in Figure 2. Nevertheless, we speculate here on the physical pathways underlying the different WAM region soil moisture-precipitation feedbacks acting in the models.

Changes in soil moisture in all models are reflected in corresponding changes in ET at the poleward edge of the climatological monsoon, where ET is limited by soil moisture (Figures 3a and 3c). Through compensating

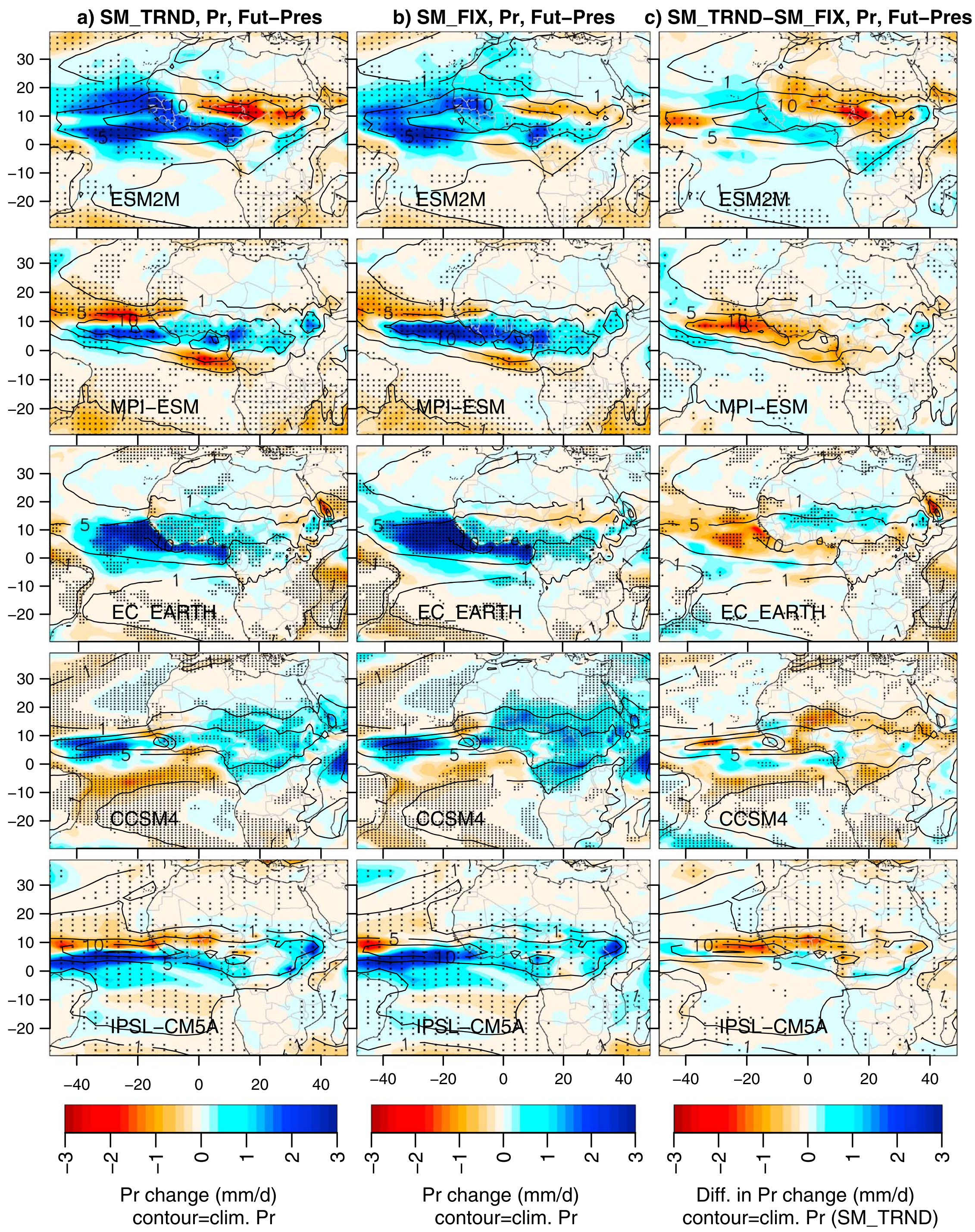

Figure 2. (a) JJAS precipitation changes in SM_TRND between 1971–2000 and 2056–2085 (shading) and present-day climatology (contour lines); (b) same as Figure 2a, in SM_FIX; (c) difference between changes in SM_TRND and SM_FIX (shading) and present-day climatology in SM_TRND (contour lines). On all panels, stippling indicates statistically significant differences. For readability, colors saturate beyond ±3 mm/d.

changes in the surface energy budget (upward longwave radiation and sensible heat flux), these changes in ET lead to changes in near-surface temperature of opposite sign over the same region (Figures 3b and 3c; note that the color bar is reversed). We expect that in arid regions, the primary influence of soil moisture anomalies on precipitation will occur through such changes in surface temperature distribution, which alter the large-scale circulation, rather than from direct influence on local water recycling. Indeed, while

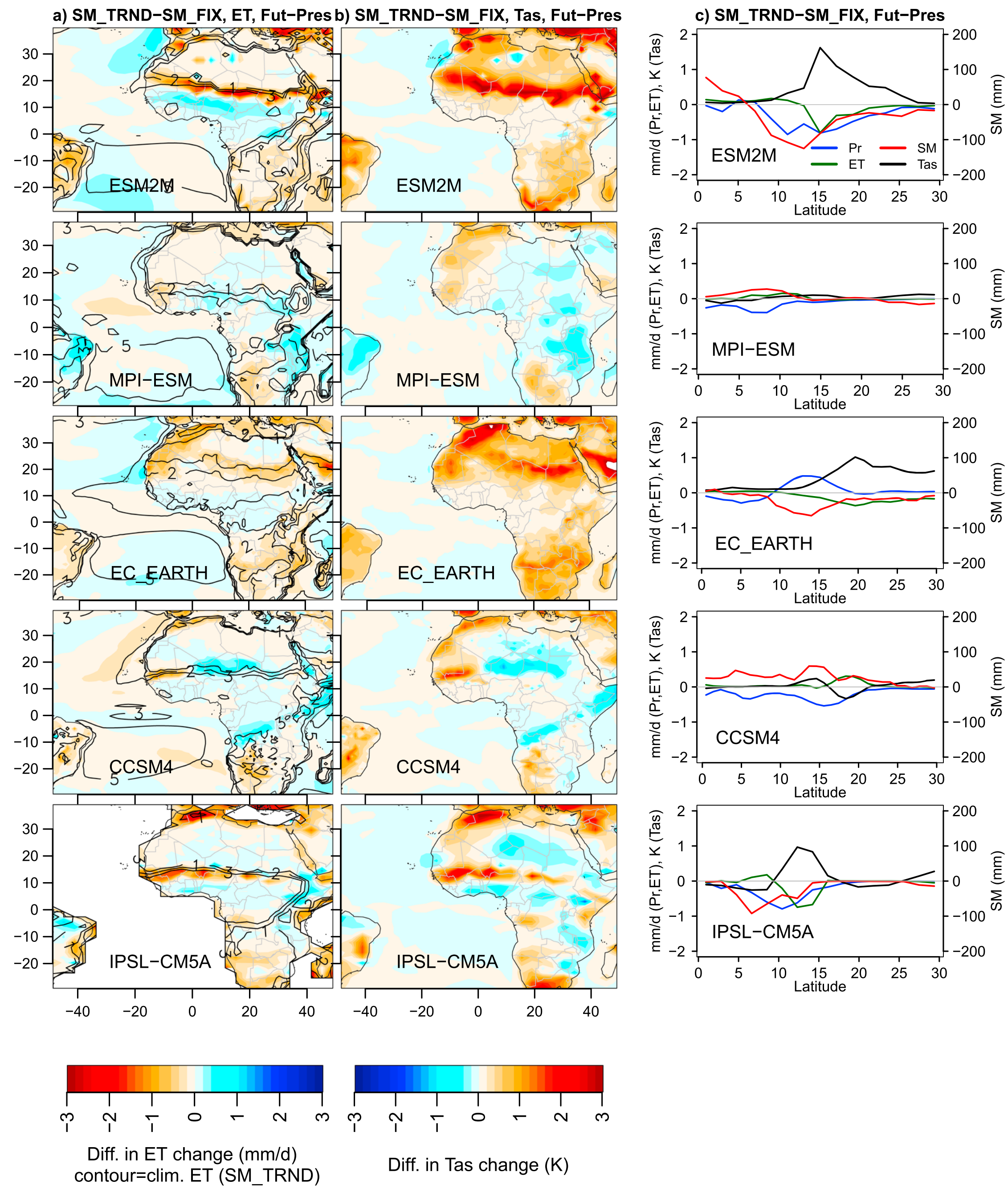

Figure 3. (a) Difference between SM_TRND and SM_FIX in future-minus-present changes in ET (mm/d, shading), and present-day ET climatology in SM_TRND (contour lines at 1, 2, 3, and 5 mm/d); (b) difference between SM_TRND and SM_FIX in future-minus-present changes in 2 m temperature; (c) difference between SM_TRND and SM_FIX in future-minus-present zonal mean changes in soil moisture (SM), precipitation (Pr), ET, and Tas (2 m temperature); zonal mean taken over −15:30°E over land.

local recycling is thought to be important in rain forest regions [*Martinez and Dominguez*, 2014; *Pokam et al.*, 2012], it is less so in drier regions [*Kong et al.*, 2013; *Arnault et al.*, 2016].

We suggest that the main mechanism acting to reduce precipitation in ESM2M and IPSL-CM5A involves surface warming at the poleward edge of the monsoon, which strengthens lower tropospheric meridional temperature gradients and displaces them equatorward. Such changes to the temperature field alter the large-scale zonal circulation over the WAM region: the midlevel African Easterly Jet (AEJ), is strengthened and displaced equatorward [*Cook*, 1999], and low-level westerlies are reduced. These circulation changes decrease precipitation in the region equatorward of enhanced warming [*Rowell et al*., 1992; *Cook*, 1999; *Rowell*, 2003; *Berg et al*., 2016b].

In EC_EARTH, on the other hand, soil moisture-induced surface warming actually occurs over the Sahara, because climatological ET extends quite far to the north in this model (Figure 3a). We suggest that the associated enhancement of large-scale thermal and pressure gradients strengthen the monsoon circulation and enhance precipitation over the Sahel in this model [*Haarsma et al*., 2005], so that opposing changes in soil moisture and precipitation appear to coexist over the Sahel. In CCSM4, on the other hand, the increase in soil moisture clearly leads to surface cooling, which is associated with locally reduced precipitation. This may reflect a negative feedback of surface cooling on precipitation in this model, as documented in similar soil moisture experiments with a previous version of the same model (CCSM3) by *Cook et al.* [2006], in a similar semiarid environment (South Africa).

Finally, in MPI-ESM, soil moisture changes are associated with very little change in ET and near-surface temperature, which is consistent with results in *Berg et al.* [2016b] and previous GLACE-CMIP5 publications. Most impacts of soil moisture change in GLACE-CMIP5 occur in arid regions, where bare ground evaporation is a large component of total ET. The absence of response in MPI-ESM is likely due to the absence of significant bare soil evaporation in that model [*Hagemann and Stacke*, 2015], which is compensated by greater evaporation from water intercepted by the canopy as well as from a surface skin layer. Such water reservoirs are not overridden in GLACE-CMIP5 and continue to respond to precipitation changes in SM_FIX and SM_TRND in MPI-ESM. Thus, because of the features of the land scheme in this model, prescribed soil moisture changes in arid regions may not affect ET, and subsequently surface climate, as in the other models.

Overall, the diversity of soil moisture feedbacks across the five GLACE-CMIP5 models analyzed here can be summarized by the zonal averages presented in Figure 3c. In all cases, the collocated ET and near-surface temperature responses are consistent with prescribed soil moisture changes, with these changes maximized along the northern edge of the prescribed soil moisture perturbation. In ESM2M and IPSL-CM5A, the precipitation response is of the same sign (negative) as prescribed changes in soil moisture; in EC-EARTH and CCSM4, they are of opposite sign. Little change occurs north of 10°N in MPI-ESM.

4. Discussion and Conclusions

Models included in the GLACE-CMIP5 experiment simulate a range of changes in Sahel precipitation in the future and as such reflect uncertainties in the broader CMIP5 ensemble. In four out of the five models (ESM2M, IPSL-CM5A, CCSM4, and EC-EARTH), future precipitation changes induced by feedbacks from projected soil moisture changes (Figure 2c) over the WAM region are comparable, in magnitude, to the response of precipitation in the absence of the soil moisture change with warming (Figure 2b). This highlights the importance of soil moisture-atmosphere feedbacks induced by long-term soil moisture changes for model projections of Sahel precipitation.

In *Berg et al.* [2016b], we demonstrated that soil moisture-atmosphere interactions associated with interactive soil moisture are an important component of the present-day coupled ocean-land-atmosphere monsoon system in West Africa, as such interactions affect both the seasonality and mean precipitation of the WAM as simulated by the GLACE-CMIP5 models. Here we have assessed changes in rainfall caused by the response of soil moisture to anthropogenic forcing, which we isolate by comparing projections from SM_FIX and SM_TRND. Note that both SM_TRND and SM_FIX include prescribed soil moisture: this comparison thus potentially neglects the additional influence of changes in the impact of soil moisture interactivity between present (such as identified in *Berg et al.* [2016b]) and future. However, such changes appear to be minor in the models; i.e., the effects of soil moisture interactivity are relatively constant between present and future (not shown). In other words, the overall long-term feedback on WAM rainfall induced by soil moisture-atmosphere interactions, in the models, is primarily associated with the feedback from changing mean soil moisture. This conclusion is consistent with *Lorenz et al.* [2016], who document little impact of soil moisture interactivity (comparing SM_TRND and SM_INT) on changes in precipitation extremes in the GLACE-CMIP5 models.

Importantly, we have identified qualitatively distinct long-term soil moisture-precipitation feedbacks in the models, with feedbacks of opposing sign. How future soil moisture change impacts the surface energy budget and near-surface temperature is qualitatively consistent across models; thus, the difference in the sign of the soil moisture feedback on precipitation appears to stem from a combination of differences in spatial patterns of surface flux and temperature changes, and the sensitivity of the atmospheric circulation and thermodynamics to these changes. Previous studies with the GLACE-CMIP5 experiment indicate mostly positive feedbacks of long-term soil moisture changes on precipitation at the global or continental scale, which have been interpreted as soil moisture amplifying precipitation changes through local moisture recycling [*Seneviratne et al.*, 2013; *May et al.*, 2015; *Berg et al.*, 2016a]. However, these studies did not investigate West Africa specifically. In this region, meridional gradients in surface temperature and pressure, which influence the monsoon circulation, are sensitive to land surface conditions [*Cook*, 1999; *Wu et al.*, 2009; *Berg et al.*, 2016b]. Projected changes in soil moisture alter local surface climate, which in turn affect large-scale circulation and precipitation remotely [*Cook*, 1999; *Haarsma et al.*, 2005]. The regional scale soil moisture-precipitation feedbacks exhibited by the GLACE-CMIP5 are thus complex. Cursory exploration of those models with negative feedbacks over the WAM (CCSM4 and EC-EARTH) does not reveal consistently negative soil moisture-precipitation feedback over other regions; our results might thus be specific to West Africa. This highlights the importance of a regional approach in assessing potentially spatially complex land-atmosphere feedback processes.

Previous research has shown that soil moisture-convection feedbacks associated with mesoscale soil moisture heterogeneities play an important role in subseasonal rainfall variability in arid regions like the Sahel [*Taylor et al.*, 2011, 2012] and that because of their coarse resolution, climate models do not simulate these interactions reliably [*Taylor et al.*, 2012, 2013]. Our results are distinct from such mesoscale soil moisture feedbacks, in that they involve larger-scale soil moisture changes and associated regional surface temperature anomalies. Our analysis points to the lack of consistency across models on the atmospheric responses even to such large-scale soil moisture changes in the context of global warming.

Previous studies have highlighted the leading role of projected SSTs and their spatial distribution in explaining the model spread in Sahel rainfall projections [*Giannini et al.*, 2013; *Park et al.*, 2015]. Our results are consistent with this view, to the extent that the projected WAM precipitation changes are qualitatively similar with and without long-term soil moisture changes (Figure 2). However, our results also highlight that soil moisture changes may significantly impact the magnitude of projected precipitation change. The limited number of models in GLACE-CMIP5 precludes more general inferences about the nature of these feedbacks in WAM projections in the wider CMIP5 ensemble. However, in light of the results presented here, systematic characterization of soil moisture-atmosphere feedbacks across models is clearly warranted. The planned inclusion of GLACE-type simulations in the upcoming CMIP6 suite (in the Land Surface, Snow, and Soil Moisture Model Intercomparison Project, LS3MIP) [*Seneviratne et al.*, 2015] should make it possible to characterize soil moisture feedbacks in a larger suite of models, as well as to analyze more comprehensively the atmospheric processes underlying such interactions. It is also critical to provide constraints on the process-level representation of these interactions in climate models. Ultimately, reducing uncertainties in simulated soil moisture-atmosphere interactions could lead to reduced uncertainties in model projections of West African precipitation with global warming.

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