The GLACE-Hydrology Experiment: Effects of Land-Atmosphere Coupling on Soil Moisture Variability and Drought Predictability

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The impact of land-atmosphere coupling on land variability is investigated using a new two-stage climate model experimental design called the “GLACE-Hydrology” experiment. First, as in the GLACE-CMIP5 experiment, twin sets of coupled land-atmosphere climate model (CAM5-CLM4.5) ensembles are performed, with each simulation using the same prescribed observed sea surface temperatures and radiative forcing for the years 1971-2014. In one set of ensembles, the land-atmosphere coupling is strongly dampened through prescription of the control model’s seasonally-evolving soil moisture climatology (‘land-atmosphere uncoupled’), enabling a contrast with the other (‘land-atmosphere coupled’). Then, the atmospheric output from both sets of simulations is used to force land-only ensemble simulations, allowing investigation of the resulting soil moisture variability and memory under both the ‘coupled’ and ‘uncoupled’ scenarios. We find that land-atmosphere coupling significantly increases soil moisture memory in the mid-latitudes and in boreal summer. The increased memory contributes primarily to a higher soil moisture variability in the US Great Plains. Consistent with the previous GLACE studies, the soil moisture-evapotranspiration (SM-ET) coupling is strongly impacted in the mid-latitude hotspot regions. Effects of precipitation variability change on soil moisture variability is surprisingly small. Soil moisture-runoff coupling also plays an important role in wet and transition regions. For the 2012 US Great Plains drought, the coupled model configuration exhibits statistically significant skill in predicting the drought but the uncoupled configuration does not. Overall, new results emphasize that land-atmosphere coupling affect land variability through a combination of the memory, precipitation variability, SM-ET coupling, and SM-R coupling processes, and they can, in certain circumstances, produce skillful prediction of a major drought.
1.0 Introduction

Understanding causes and predictability of drought is of societal importance (Cheng et al. 2016; Evans et al. 2017; Held et al. 2005; Hoerling et al. 2014; Livneh and Hoerling 2016). The 2012 drought was the most extensive US drought in the instrumental record from 1895 to the present and resulted in $30 billion economic losses, largely from the agricultural sector (Hoerling et al. 2014; Rippey 2015). Many investigators have highlighted the importance of the remote oceanic forcing on drought development and prediction (Ault et al. 2018; Hoell et al. 2016; Kam et al. 2014; Swain 2015; Wang et al. 2014; Wei et al. 2016). Hoerling et al. (2014) attributed the 2012 drought to natural climate variability. A synthesis study also revealed limitations in large-scale SST-driven predictability of droughts. The study suggests that additional sources of predictability should be explored, including land-atmosphere coupling (Schubert et al. 2016).

A significant precipitation deficit relative to normal causes a “meteorological drought”. An “agricultural drought”, however, instead is better measured by the resulting soil moisture deficit (Sheffield and Wood 2011), which also incorporates effects of the land processes, e.g., soil moisture memory, snow melt, runoff, and evapotranspiration. Soil moisture exhibits considerably higher memory than precipitation, so soil moisture memory can potentially contribute to drought predictability (Amenu et al. 2005; Guo et al. 2012b; Kumar et al. 2014b; Orth and Seneviratne 2013; PaiMazumder and Done 2016), including through a climate process called “soil moisture anomaly reemergence” described by (Kumar et al. 2019). The study showed that root zone soil moisture anomalies can recur several seasons or more than a year after they were initiated, indicating potential inter-annual predictability. However, the impact of land-atmosphere coupling on soil moisture variability is not thoroughly investigated.

In addition to local soil moisture feedbacks, land-atmosphere coupling can also affect global circulation patterns, for example by warming the near surface air temperature (Berg et al.
2014; Delworth and Manabe 1988), and the resulting circulation changes may feedback onto precipitation anomalies in the Great Plains (Schubert et al. 2008). In the continental US, a dry surface soil moisture anomaly can generate circulation anomalies by creating a high over the west-central US, with a low to its east, further strengthening central United States warming and drying (Koster et al. 2016). Teng et al. (2019) found a robust circumglobal response due to heating anomalies induced by the synthetic drought in the continental United States.

Our study is motivated by the hypothesis that land processes and their coupled interactions with the atmosphere can enhance drought predictability beyond what is predictable from the SST forcing alone. We posit three principal mechanisms: (1) climate forcing remote pathway, where soil moisture anomalies drive changes in the remote circulation patterns and thereby modify advection of atmospheric moisture into or out of the region (Koster et al. 2016; Schubert et al. 2008); (2) climate forcing local pathway, where soil moisture anomalies influence boundary layer growth, clouds, and precipitation triggering (Findell and Eltahir 2003; Santanello Jr et al. 2018; Tawfik and Dirmeyer 2014); and (3) land processes pathway, where local processes control soil water availability including evapotranspiration, runoff, soil moisture memory and reemergence. Collectively, these three mechanisms are considered to be land-atmosphere coupling effects in this study. Importantly, land-atmosphere coupling is stronger during summer when the predictability due to large-scale remote oceanic forcing appears to be limited (Dirmeyer 2011; Koster et al. 2004; Seager and Hoerling 2014; Seager et al. 2015).

We suggest that the impact of land-atmosphere coupling on drought has been generally underestimated in earlier studies that used observed atmospheric forcing (anomalous precipitation and temperatures) to force land surface models in an uncoupled configuration (Livneh and Hoerling 2016; Luo et al. 2017; Williams et al. 2015). More generally, agricultural drought was
mainly attributed to precipitation deficits, which have limited predictability (Deser et al. 2012a; Deser et al. 2012b; Hoerling et al. 2014). However, such studies cannot isolate the impact of the land-atmosphere coupling on the observed precipitation and temperature anomalies themselves and hence cannot gauge its importance to drought.

On the other hand, a rich literature exists that emphasizes the effects of land-atmosphere coupling on precipitation and temperature variability. The Global Land-Atmosphere coupling experiment (GLACE) phase 1 isolated the impact of interactive soil moisture on precipitation variability in a multi-model framework (Koster et al. 2004; Koster et al. 2006). The GLACE-CMIP5 experiments extended the GLACE experiments to the Coupled Model Intercomparison Project – Phase 5 climate models. They found a stronger influence of the land-atmosphere coupling on extreme daytime temperature than mean temperature while its effects on precipitation were less robust (Seneviratne et al. 2013; Taylor et al. 2012). Orth and Seneviratne (2017) found that land-atmosphere coupling increase temperature variability in the warm season by 10 to 50%, similar in magnitude to the impacts of SST anomalies.

A knowledge gap exists in investigating combined effects of the land-atmosphere coupling on climate forcing anomalies, the soil moisture memory process, and an overall intensification or amelioration of the “agricultural drought.” Our new two-stage experimental design, referred to here as the *GLACE-Hydrology Experiment*, addresses this knowledge gap (Figure 1). First, as in the GLACE-CMIP5 experiment, twin sets of coupled land-atmosphere climate model (CAM5-CLM4.5) ensembles are performed, with each simulation using the same prescribed observed sea surface temperatures and radiative forcing for the years 1971-2014. In one set of ensembles, the land-atmosphere coupling is strongly dampened through prescription of the control model’s seasonally-evolving soil moisture climatology (‘land-atmosphere uncoupled’), enabling a contrast
with the other (‘land-atmosphere coupled’) set of ensembles. Then, the atmospheric output from both sets of simulations is used to force land-only ensemble simulations, allowing investigation of the resulting soil moisture variability under both the ‘coupled’ and ‘uncoupled’ scenarios. This experimental design has the following advantages: (1) an internally consistent set of climate modeling experiments, i.e. we used the same land surface model (CLM4.5) in Stage 1 and 2 of the experiment; (2) impacts of the land-atmosphere coupling on climate forcing can be isolated; and (3) combined effects of co-evolving climate forcing and soil moisture anomalies can be investigated.

There are considerable uncertainties in the representation of the land processes, vegetation parametrizations, and soil moisture-atmosphere coupling in climate models (Dahlin et al. 2015; de Noblet-Ducoudre et al. 2012; Dirmeyer et al. 2006; Dirmeyer et al. 2013; Ferguson et al. 2012; Guo and Dirmeyer 2006; Kumar et al. 2013b; Liu et al. 2017; Pitman et al. 2009). In general, CAM5-CLM4 exhibits relatively weak land-atmosphere coupling when compared to the observational and reanalysis-based coupling strength estimates (Mei and Wang 2012). Still, many studies have employed the NCAR climate model to conduct climate predictability studies (Dirmeyer et al. 2013; Infanti and Kirtman 2016; Kumar et al. 2014b; Yeager et al. 2018). The Community Earth System Model – Large Ensemble data is an additional resource to compare the effects of the land-atmosphere coupling with that of externally forced climate change signal and internal climate variability (Kay et al. 2015).

This paper is organized as follows: Section 2 describes the experimental design, data, and methods. Next, to place the drivers of the soil moisture variability in our experiment setup in context, we describe a simple soil moisture variability model in Section 3. Section 4 presents results, which are divided into three main sub-categories: (a) characteristics of the GLACE-
Hydrology experiment that help us to interpret the remaining results, (b) changes in the soil moisture variability and its drivers, and (c) implications for the 2012 Great Plains drought. Finally, a discussion is presented in Section 5 that also covers key conclusions from this study.

2.0 Data and Methods

a. The GLACE-Hydrology Experiment Design

Our experimental design follows the Global Land-Atmosphere Coupling Experiment methodology (GLACE and GLACE-CMIP5) (Koster et al. 2004; Seneviratne et al. 2013) with the addition of subsequent land-only experiments aimed at isolating the soil hydrology responses to land-atmosphere coupling (Figure 1 and Table 1). Based on atmospheric General Circulation Model (GCM) simulations whose ocean boundary conditions are specified from observations, i.e. a standard AMIP (Atmospheric Model Intercomparison Project) style run, we conduct two sets of model runs: (1) an ensemble of control runs in which the land and atmosphere are interactively coupled (LA-coupled ATM), and (2) an ensemble of experimental runs in which the land-atmosphere coupling is muted by specifying the seasonally-evolving soil moisture climatology extracted from the control run; that is, removing the effects of anomalous soil moisture interactions with the atmosphere (LA-uncoupled ATM). We then use the three-hourly atmospheric forcing data archived from both sets of ensembles to run land-only simulations, LA-coupled LAND, and LA-uncoupled LAND, allowing for consistent comparison of the soil moisture variability associated with and without the land-atmosphere coupling.

We implemented the GLACE-Hydrology experiment in the Community Earth System Modeling framework (CESM) (Hurrell et al. 2013) using the Community Atmospheric Model version 5 and Community Land Model version 4.5 (CAM5+CLM4.5), and performed \(2 \times 10^2\) member ensemble experiments forced by the observed monthly sea surface temperature data from 1971 to 2014 (Hurrell et al. 2008) as the oceanic boundary condition. Each ensemble member was
created by a small random perturbation to atmospheric initial conditions using the same method as in CESM-LE (Kay et al. 2015). The same land model initial conditions, taken from a transient land-only CLM4.5 simulation with the Climate Research Unit and the National Center for Environmental Prediction (CRUNCEP) forcing, are used in all the simulations. One of our goals is to simulate observed drought events, hence we used transient climate simulations with the greenhouse gas forcing and land use change. For each ensemble member, we first perform the control experiment, and then use its soil moisture climatology to make the corresponding LA-uncoupled ATM simulation. The three-hourly atmospheric data from each ensemble member, having been saved, is then (in stage 2) used to force the corresponding land-only simulation.

Table 1 provides the list of variables analyzed and the corresponding experiment ID. In general, Stage 1 (ATM) provides the surface atmospheric forcing variables, temperature and precipitation, and Stage 2 (LAND) provide the response variables, evapotranspiration and soil moisture, the main focus of this study. Table 1 also compares the key features of the GLACE-Hydrology experiments with the standard CLM offline experiment using observed atmospheric forcing (Oleson et al. 2013; Quéré et al. 2018), and the CESM Large Ensemble experiment (Kay et al. 2015). For example, the GLACE-Hydrology experiment uses observed SST, whereas the CESM-LE uses the model generated SST that may not be correlated in time with the observation. This feature has implications for simulating observed drought events (discussed later).

b. Community Land Model

The CLM4.5 has a 10-layer fixed depth soil moisture scheme, which extends down to 3.8m depth. It solves the one-dimensional Richard’s equation within each soil column, which can share several plant functional types to account for vegetation heterogeneity at the surface. Plant functional types describe vegetation structure in terms of leaf properties, canopy heights, and root distributions.
CLM also has a prognostic seasonal cycle of vegetation evolution, emergence and senescence of leaves, and vegetation heights based on the Biome-biogeochemical cycle model (Thornton and Rosenbloom 2005; Thornton et al. 2002).

We implemented a modified version of the GLACE-CMIP5 design (Seneviratne et al. 2013) to specify soil moisture climatology. This scheme reduces temperature variability biases in high latitudes in the LA-uncoupled ATM experiments (Figure 2(a)). The modified scheme adjusts liquid and ice fractions of total soil water that is consistent with the meteorological conditions at the current time step in the model. This takes liquid and ice fraction in the current time step and distributes the seasonal climatology of total soil water accordingly. We found that the GLACE-CMIP5 scheme where liquid and ice fractions were set to seasonal climatological values was creating an extra heat sink, specifying a larger fraction of ice content than desired. This extra heat melted the ice too much, resulting in a larger temperature mean and variability biases between the LA-coupled and LA-uncoupled ATM experiments. The modified scheme removed the temperature mean and variability biases in the high latitudes (Figure 2(a), and Supplementary Figure S1).

c. Statistical Methods

We have used a Monte Carlo method to compute the statistical significance of the variance and correlation differences between the LA-coupled and LA-uncoupled experiments. For example, we applied the following steps for the significance calculation of the soil moisture and ET correlations:

1. compute the correlation for each month and each ensemble member separately using monthly anomalies data from 1979 to 2014,
2. make a mixed pool of 20 ensemble members (10 from the LA-coupled LAND and 10 from the LA-uncoupled LAND),
3. randomly select, with replacement, two groups of 10 ensemble member from the mix pool, and compute their differences, and
4. repeat the process 1000 times and sort the range of the differences. If the
difference between the LA-coupled LAND and LA-uncoupled LAND experiments fall outside the 95% range of the random sample in the given month, then the result is statistically significant.

3.0 A simple model for soil moisture variability

To better comprehend the complexities of the land-atmosphere coupling and its impact on soil moisture variability, let us consider the following simple model for the monthly variation of soil moisture anomalies:

\[ S'_t - S'_{t-1} = P'_t - ET'_t - R'_t, \]

where the left-hand side represents the change in soil moisture anomalies \( S' \) over the time interval \([t - 1, t]\), and \( P'_t \), \( ET'_t \), and \( R'_t \) are the accumulated anomalous precipitation, evapotranspiration, and runoff, respectively, during that time interval. Anomalies are determined relative to the long-term monthly climatology. Multiplying both sides by \( S'_t \), taking a time average, and rearranging terms, yields a budget for soil moisture variance:

\[ \overline{S'_t S'_t} = \overline{S'_{t-1} S'_{t-1}} + \rho_{P'_t S'_t} \sigma_{P'_t} \sigma_{S'_t} - \rho_{ET'_t S'_t} \sigma_{ET'_t} \sigma_{S'_t} - \rho_{R'_t S'_t} \sigma_{R'_t} \]

Expressing all the covariability terms \( \overline{X'Y'} \) in terms of correlation coefficients \( (\rho_{XY}) \) and corresponding standard deviations \( (\sigma_X \text{ and } \sigma_Y) \), such that \( \overline{X'Y'} = \rho_{XY} \sigma_X \sigma_Y \), (2) becomes

\[ \sigma_{S_t} = \rho_{S_tS_{t-1}} \sigma_{S_{t-1}} + \rho_{P_tS_t} \sigma_{P_t} - \rho_{ET_tS_t} \sigma_{ET_t} - \rho_{R_tS_t} \sigma_{R_t} \]

The first term on the right-hand side represents the effect of soil moisture memory, modulated by the seasonal cycle of soil moisture variability (that is, when \( \sigma_{S_t} = \sigma_{S_{t-1}} \)). The second term is the soil moisture-precipitation (SM-P) coupling, which for positive correlation acts to increase soil moisture variability. The final terms are the soil moisture-evapotranspiration (SM-ET) coupling and soil moisture-runoff (SM-R) coupling, which for positive correlations each act to decrease soil moisture variability. Although all these terms are interactive (that is, they can feed back to each
other, e.g. soil moisture and precipitation feedback), (3) can be used in a diagnostic sense to quantify the relative influence of each of the four terms on soil moisture variability.

We use (3) rather than (2) because its terms can be easily related to other land-atmosphere coupling studies. For example, previous GLACE studies have mainly investigated the soil moisture-evapotranspiration coupling term and its impacts on precipitation and temperature variability (Guo et al. 2006; Koster et al. 2010; Koster et al. 2004; Koster et al. 2006). Keeping all other factors the same, increasing soil moisture-evapotranspiration coupling ($\rho_{ET_{st}}$) is expected to decrease soil moisture variability, which is supported by observations (Teuling and Troch 2005). Similarly, soil moisture memory ($\rho_{S_{st-1}}$) has been extensively studied (Amenu et al. 2005; Dirmeyer et al. 2016; Entin et al. 2000; Koster and Suarez 2001; Nicolai-Shaw et al. 2016; Orth and Seneviratne 2012; Vinnikov et al. 1996; Wu and Dickinson 2004; Wu et al. 2002). These studies have found that the root zone soil moisture memory time scale ranges from 2-4 months.

We are interested in investigating the co-evolution of all four terms in an internally consistent climate modeling experiment, and identifying their relative importance for drought predictability.

We use one-month lag correlation for total soil moisture (3.8m depth in CLM4.5) and its inter-annual standard deviation in our calculation. Total soil moisture depth is necessary to be consistent with the remaining terms in equation 3 that represent total precipitation, evapotranspiration, and runoff variabilities. Accordingly, the memory and variability differences are computed using total soil moisture. Using only the root zone soil moisture (0-1m) does not change any interpretation of our result, but the variance budgets do not close because the root zone does not account for all water available in the soil column.

4.0 Results
We first describe the experimental characteristics that aid in understanding how soil moisture variability changes due to land-atmosphere coupling, as well as provide context for this study vis-à-vis the existing GLACE literature. Next, we present effects of the land-atmosphere coupling on soil moisture variability and soil moisture memory. Then, we decompose the total soil moisture variability changes due to land-atmosphere coupling by the four driver climate processes discussed previously. Finally, our approach is applied to the specific case of the 2012 Great Plains drought, which we use as a test bed to compare and contrast the land-atmosphere coupling effects with those of SST forcing and climate change effects.

4.1 Characterization of the GLACE-Hydrology Experiment

4.1.1 Hydroclimate Variability

The land-atmosphere coupling increased the temperature and ET variability in low to mid-latitude regions and in the summer. Figure 2 shows the zonal mean, taken over land only, of near surface air temperature and ET variability from ATM and LAND experiments, respectively, for both the coupled and uncoupled ensembles in the boreal summer season (JJA). Land-atmosphere coupling significantly increased surface air temperature variability in the low and mid-latitude regions, consistent with previous studies (Berg et al. 2014; Delworth and Manabe 1988). We find from the LAND experiments that land-atmosphere coupling increased evapotranspiration (ET) variability, mainly for the mid-latitudes (30°N to 60°N). There is also a slight increase in ET variability between 20°S and the equator.

Figure 2(a) also shows one ensemble member (gray line) from an experiment using the soil moisture seasonal climatology scheme as in the GLACE-CMIP5 in the LA-uncoupled ATM experiment. The GLACE-CMIP5 scheme shows a decreased temperature variability in the high
latitudes (60°-80°N). This decrease in the high-latitude temperature variability is completely
removed in the new scheme applied in this study.

The land-atmosphere coupling dynamics shift to the southern hemisphere in the austral
summer. Figure 3 shows the temperature and ET variability during the DJF season. As expected,
the land-atmosphere coupling effects shifted to the Southern Hemisphere. Areas between 40°S and
10°S show increased temperature variance due to the land-atmosphere coupling. The
evapotranspiration variance did not change in the DJF, perhaps because mid-latitude inland areas
are small in the Southern Hemisphere. Since stronger land-atmosphere coupling effects are found
in the JJA season, the remainder of the paper presents results for only the JJA season.

Geographically, both the increasing and decreasing ET variability responses due to land-
atmosphere coupling are found. Figure 4(a) shows the spatial pattern of ET variability changes,
which significantly increases for 25% land area and decreases for 11% land area. Note that we
show difference maps here and all the remaining analysis in dimensional units (e.g., mm/month
for ET change), instead of as a relative change (e.g. percentage difference). The dimensional unit
difference map representation can make sometime even a small change statistically significant if
the corresponding total quantities are small, e.g. evapotranspiration changes in the Sahara desert.
The mid-latitude regions, e.g. Central North America and Southern Europe and Eurasia, sub-
tropical regions, e.g. central Asia and parts of India (IND), and certain regions in the Southern
Hemisphere all show increased ET variability, while the northern part of the Sahel (SAH), Amazon
and Congo basins all show decreased ET variability. Overall, as expected, land-atmosphere
coupling increases ET variability mainly in the mid-latitude regions.

We compare the spatial pattern of ET variability changes with that of precipitation
variability changes. Figure 4(b) shows the spatial pattern of precipitation variability changes,
which significantly increases for 19% land area and decreases for 23% land area. Most of the increase in precipitation variability occurs in wet regions (e.g. the eastern US, India, south-east Asia, northeastern China, and the northern part of the Congo, and north of the Amazon basins), while decreases occur in dry regions (e.g. Sahel, Mediterranean Europe, the western United States, central Canada, South Africa, and the southern Amazon). Note that in the mid-latitudes significant changes in ET variability generally do not coincide with regions of significant changes in precipitation variability, suggesting that different climate processes drive changes to each variable.

The land-atmosphere interactions play a larger role in the ET variability, and circulation changes are likely to play a role in the precipitation variability. Because previous studies have found a less robust effects of land-atmosphere coupling on precipitation than temperature that is a key driver of ET (Guo et al. 2012a; Guo et al. 2006; Seneviratne et al. 2013). We have discussed this issue in Appendix 1: Changes in mean climate because we will show later that the precipitation variability change is not the primary driver of soil moisture variability change.

An analysis similar to Figure 4 for the DJF season, shown in the Supplementary (Figure S2) finds considerably reduced impacts due to the land-atmosphere coupling, consistent with Figure 3.

4.1.2 Land-Atmosphere Interactions

The simultaneous correlation of soil moisture and evapotranspiration (SM-ET) anomalies is one of the fundamental metrics used to assess land-atmosphere coupling (Dirmeyer 2011; Guo et al. 2006; Koster et al. 2006). Consistent with the previous study by (Dirmeyer 2011), the LA-coupled LAND experiment (Figure 5a) captures the spatial pattern of significant positive correlations in dry and transition regions, including the central and western US, the southern part of the Europe and Eurasia, central Asia, and the Sahel in the Northern Hemisphere. Wet regions, such as India,
Southeast Asia, eastern US, and the northern high-latitude regions in North American and Europe, show negative correlations. A negative SM-ET correlation can suggest that soil moisture anomalies are mainly driven by precipitation anomalies that are associated with increased cloud cover anomalies, thereby also reducing net radiation and therefore the evapotranspiration (Tang and Leng 2013).

A new result from the GLACE-Hydrology experiment is a quantitative assessment of the fundamental metric the SM-ET correlation difference between the coupled and uncoupled experiment. The land-atmosphere coupling appears to significantly enhance the amplitude of SM-ET correlations especially in the hot-spot regions. This is true both for positive correlations in the midlatitudes, especially in central North America and southern Europe and Eurasia, and negative correlations in the Tropics, including India, parts of Southeast Asia, central Africa, and South America (Figure 5b). There are mixed responses in the Sahel. Note that this land-atmosphere coupling sensitivity is found only in some specific regions that generally coincide with the “hot-spot” regions for the land-atmosphere coupling (Koster et al. 2004). The strongest impacts of the land-atmosphere coupling are found in the central North America and Southern Europe and Eurasia regions, where the difference is of the same order of magnitude as the total SM-ET correlations in the LA-coupled LAND experiment (Figure 5). Other regions, e.g. throughout the western North America do not show similar sensitivity to the land-atmosphere coupling. In other words, in the absence of available soil moisture, capacity of the dry regions to module the ET variability is limited. We repeated our analysis using the terrestrial coupling index metric developed by (Dirmeyer 2011), and found similar results (supplementary Figure S3). We have discussed implication of this new result in Section 5.

4.2 Land-atmosphere coupling effects on soil moisture variability and memory
The land-atmosphere coupling increased the soil moisture variability significantly for 18% land area, including parts of the central US, central Asia, and southern Sahel, tropical regions of Africa, Asia, and South America, and decreased for 11% land area, including parts of the central North America, Southern Europe and Eurasia, and southeastern Asia regions (Figure 6a). The changes are not consistent within any region, however, with significant increases and decreases often side by side, e.g. the Midwestern United States and its adjoining region in the east.

Effects on soil moisture memory is more spatially coherent with an overall increase in memory especially in the mid-latitude regions (Figure 6b). Figure 6b shows soil moisture memory difference between the LA-coupled LAND and the LA-uncoupled LAND experiments, where soil moisture memory is defined using the one-month lag correlation ($\rho_{S(t)S(t-1)}$). The land-atmosphere coupling increased soil moisture memory in the mid-latitudes (significantly in 12% of the land area), e.g. Central North America and southern Europe and Eurasia, and decreased the memory in tropical regions (significantly in 7% of the land area), especially central Africa and the northern Amazon. The increase in the memory appears to be driven by the land-atmosphere coupling response (see the correspondence between Figure 6b, and Figure 5b for the central North America, and southern Europe and Eurasia). Whereas, the memory decrease can be driven by precipitation variability changes (discussed later).

### 4.3 Drivers of the soil moisture variability change due to land-atmosphere coupling

The pattern of soil moisture variability change in Figure 6a does not simply correspond to changes in any one term in equation 3. For example, in the mid-latitudes increased SM-ET correlations (Figure 5b) does not always correspond to decreased soil moisture variability. Similarly, in some regions (e.g. India and the eastern US) increased precipitation variability (Figure 4b) correspond to decreased soil moisture variability. Changes in soil moisture variability...
and precipitation variability are also of opposite sign in southern Africa and the southern Amazon basin. Overall, effects of land-atmosphere coupling on both sources (precipitation) and/or sinks (evapotranspiration) and SM-ET correlations (Figures 4 and 5b) are not sufficient to explain the soil moisture variability changes in the experiment, suggesting that changes to soil moisture memory must also be important.

We next use eqn. (3) to diagnose how land-atmosphere coupling drives the soil moisture variability changes seen in Figure 6a. Figure 7 shows the corresponding changes in the four components of (3): soil moisture memory, SM-P coupling, SM-ET coupling, and SM-R coupling terms. The SM-P coupling term constitute of two quantities: (1) SM-P correlations ($\rho_{P_tS_t}$) that do not change significantly due to land-atmosphere coupling (Supplementary Figure S4), and (2) P-variability ($\sigma_{P_t}$) that gets affected by the land-atmosphere coupling, hence we have referred SM-P coupling as the *forcing term* in the remaining discussion. We first compute each of the four terms of equation 3 separately for the LA-coupled LAND and LA-uncoupled LAND experiment for each month, and then we compute the difference between the coupled and uncoupled experiments. The statistical significance of the difference is computed using the Monte-Carlo method. We have multiplied each term by their sign in equation 3, so that the sum of all four panels in Figure 7 equals Figure 6a. It is worth noting that, even if we performed all the calculations using monthly data, the residual terms are very small (Supplementary Figure S5).

Despite the importance of changes to covariability of soil moisture with its sources (P) and sinks (ET), the memory term ($\rho_{S_tS_{t-1}} \sigma_{S_{t-1}}$) is the largest contributor to the increased soil moisture variability in many regions (Fig. 7a). Both terms, the memory ($\rho_{S_tS_{t-1}}$) and the variability ($\sigma_{S_{t-1}}$) has increasing tendency in the coupled experiment, generally (Figure 6). Hence, with the increased memory, the coupled experiment was able to bring in a larger soil moisture variability
contribution from the previous month \((t - 1)\) to the current month \((t)\) compared with the smaller memory and variability in the LA-uncoupled experiment.

The effect of land-atmosphere coupling on precipitation variability had a somewhat surprisingly weak impact on soil moisture variability, apart from some regions in and near the Tropics (India and central Africa; Figure 7b). The soil moisture and precipitation correlations also did not change significantly (Supplementary Figure S4).

As expected, the SM-ET coupling terms mainly contributed to decrease soil moisture variability in the mid-latitudes, e.g. central North America, and southern Europe and Eurasia (Figure 7c). The SM-ET coupling terms increased soil moisture variability in the tropical regions, e.g. India and northern Amazon basin. This was also an expected response because SM-ET correlations are negative in wet regions (Figure 5b).

The SM-R coupling term contributed to an increase in soil moisture variability in the transition region, e.g. parts of central North America, Sahel regions, and a decrease in the wet region, e.g. India, and Southeast Asia (Figure 7d). We investigated the SM-R correlation \((\rho_{RS_t})\) and runoff variability \((\sigma_{R_t})\), separately. We found that the runoff variability significantly decreased due to land-atmosphere coupling in the transition region, and increased in the wet region (Figure 8), whereas the SM-R correlation did not change significantly (Supplementary Figure S6).

In other words, the SM-R coupling term mainly contributed through the changes in the runoff variability.

A physically plausible explanation for the runoff coupling term can be as follows: the SM-R coupling term increases soil moisture variability in the transition region by slowing water drainage from the soil, and therefore decreases the runoff variability. The SM-R coupling term decreases the soil moisture variability in the wet region because of reduced infiltration due to
saturated conditions and therefore a higher partitioning of precipitation into runoff than into the soil, and therefore increase in the runoff variability (Niu et al. 2005).

Four terms of equation 3 can be equally important but in different regions. Figure 9 shows regional contributions of the memory, forcing, SM-ET coupling, and SM-R coupling terms, averaged within the two contrasting region in the mid-latitudes: the Midwest US (MW-US) and the Central East US (CE-US), and two in tropical/sub-tropical climate: the Central West Sahel (CW-SAHL), and Central-West India (CW-IND). In the MW-US, the memory term is the largest contributor to the increased soil moisture variability. The relative influence of SM-ET coupling term is negative and ~3 times smaller than that of memory term. In the CE-US, the SM-ET coupling is the largest contributor to an overall decrease in soil moisture variability.

In the tropical/subtropical regions, the forcing term plays a larger role but it is generally counterbalanced by the SM-R coupling term. For example, the forcing term increases soil moisture variability in CW-IND by making it wetter (Appendix 1), but it was balanced by the SM-R coupling term, resulting into only small increase in soil moisture variability. Similarly, in the CW-SAHL, a decreased forcing variability was balanced by the increased SM-R coupling term, resulting into a smaller decrease in soil moisture variability that seems to be contributed by the decrease in the memory term (Figure 7a). While the SM-ET coupling term has received more attention in the previous GLACE studies (Dirmeyer 2011; Guo et al. 2006; Koster et al. 2004; Koster et al. 2006); figure 9 shows that the memory term, and SM-R coupling terms can play an equally important role for the soil moisture variability. This is the second unique contribution of the inclusion of the land-only simulations in the GLACE-Hydrology experiment.

4.5 Comparison of the land-atmosphere coupling and the climate change effects during the 2012 Great Plains drought
We compared the 2012 Great Plains drought anomalies in (1) observations, (2) LA-coupled, (3) LA-uncoupled, and (4) the 40-member CESM Large Ensemble (CESM-LE) fully coupled simulations (Figure 10). Using the CESM-LE permits assessment of the contribution of the forced climate change signal, although the evolution of SST anomalies is different than in the other three datasets. The difference between the LA-coupled and LA-uncoupled experiments is directly attributable to the land-atmosphere coupling effects. The LA-uncoupled experiment provides the SST forcing only effects. We use CLM4.5 land-only experiment with the observed climate forcing (CRUNCEP) as our synthetic observations. The spatial extent of the 2012 drought is captured by the synthetic observations (Figure 10a) and it compares well with the US Drought monitor (Supplementary Figure S7), as well as with the hydrologically constrained Variable Infiltration Capacity model (Livneh and Hoerling 2016).

To make the analysis consistent across the models and observations, we use a mean standardized departure metric \( MSD = \frac{X - \bar{X}}{std(X)} \), calculated with respect to each member climatology \( \bar{X} \) and standard deviation \( std(X) \). Note that both the climatology and the standard deviations, calculated using the base period from 1981 to 2010, can differ in the respective climate simulations. We also tested the hypothesis that the ensemble average MSD anomalies are significantly different from zero using a standard t-test. Following (Livneh and Hoerling 2016), we define the core Great Plains region as the region bounded by 36°-43°N and 90°-105°W (Figure 10).

The LA coupled LAND experiment captures the 2012 drought across the US skillfully (Figure 10). Whereas, the LA uncoupled LAND experiment shows limited skill in capturing the 2012 drought, especially in the Great Plains. The CESM-LE experiment does not show skill in the 2012 drought prediction. This is an expected response because SST condition in the CESM-
LE are not correlated with the observed SST. Next, we diagnose sources of the drought predictability in the Great Plains.

The observed precipitation anomaly during the 2012 drought is compared to the results of the three different model configurations in Figure 11a. Of the three, the ensemble range of the LA-coupled ATM experiment is able to capture the observed precipitation anomalies. While the observed precipitation anomaly is considerably stronger than that of the LA-coupled ATM experiment ensemble mean, it is well within the ensemble spread. However, without land-atmosphere coupling (the LA-uncoupled ATM), the SST forcing alone was insufficient to capture the 2012 drought. Results were worse for the CESM-LE, which may have been able to represent land-atmosphere coupling and a climate change signal but did not have the observed SST anomalies. These results all suggest that both observed anomalous SST forcing and land-atmosphere coupling were key components of the 2012 drought.

The predictable drought signals of precipitation anomalies were small and not statistically significant in both the LA-coupled and LA-uncoupled experiments. Overall, the ensemble average LA-coupled ATM experiments captures 23% (p-value: 0.12) of the observed precipitation anomalies, whereas the LA-uncoupled experiment captures only -7% (p-value: 0.22) and even of opposite sign from the observed precipitation anomalies. A smaller precipitation signal in the LA-coupled ATM experiment is expected because of a larger role of the internal atmospheric variability than the SST forcing particularly in the Great Plains (Hoerling et al. 2014). For example, Seager and Hoerling (2014b) found that SST forcing can explain only 10% of the observed precipitation variability in the Great Plains.

Figure 11b shows soil moisture anomalies during the 2012 drought. In the LA-coupled LAND experiment, the ensemble-mean signal was statistically significant and much closer to
“observations”, reaching 85% (p-value: 0.00016) of the observed soil moisture anomaly (-1.16 MSD). Note that despite the large ensemble spread of precipitation forcing (Figure 11a), almost all ensemble members show soil moisture drying (MSD < 0) in the LA-coupled LAND experiment. In contrast, the LA-uncoupled experiment does not show a statistically significant skill (p-value: 0.17) for the agricultural drought.

Given the discussion presented in Section 3.3, we might ask whether the memory term is acting to enhance Great Plains soil moisture drought predictability in the coupled experiment. An applicable form of equation 3 for the Great Plains region is given below where the corresponding correlation terms are computed using the LA-coupled LAND experiment data for the entire simulation period from 1979 to 2014.

\[
\sigma_{S_t} = (0.88 \pm 0.00) \sigma_{S_{t-1}} + (0.31 \pm 0.01) \sigma_P - (0.38 \pm 0.01) \sigma_{ET_t} - (0.43 \pm 0.01) \sigma_R_t
\]  

(5)

It is evident that the memory term is the largest contributor to soil moisture variability for a unit change in the corresponding standardized anomalies. We integrated equation 5 for the 2012 drought by replacing the standard deviations with the corresponding mean standardized departure anomalies in the given month for P, ET, and R, and previous month soil moisture. The JJA average results show a major contribution from the memory term (-0.80±0.15) and a minor precipitation forcing effect (-0.11±0.06) during the 2012 Great Plains drought. Thus, the memory term contributes 69%, and the forcing term contributes 9% to the total observed anomalies (-1.16 MSD).

Since we expect a higher soil moisture memory during a drought event, causing us to believe that our estimate of the memory term is conservative.

A similar calculation using data from the LA-uncoupled LAND experiment shows significantly reduced contribution of the memory term (-0.18±0.15), and the forcing term
(0.00±0.03) (Figure 12b). Hence, it is concluded that the memory term contributed to improve the soil moisture anomalies prediction skill in the LA-coupled LAND experiment.

We repeated our analysis presented in Figure 11b for the root zone (0-1m) soil moisture anomalies only, and found a statistically significant skill that captured 58% (p-value: 0.008) of the observed root zone soil moisture anomalies (-1.2 MSD) in the Great Plains. A slight reduction in the signal strength is expected from a shorter memory in the root zone compared to the full soil column (Kumar et al. 2019).

Contributions from the external forcing (CESM-LE ensemble) mean are statistically significant but of opposite sign for the precipitation anomalies, and are not statistically significant for the soil moisture anomalies (Figure 11). Hence, we conclude that the climate change had minimal contributions to the 2012 drought. However, we note that the impact of external forcings could change under higher emission scenarios in the future climate (Kumar et al. 2014a; Maloney et al. 2014).

Motivated by the encouraging results for 2012 drought, we also performed similar analysis for five other major drought events in the Great Plain (Figure 12). These drought events arranged in the order of their severity using precipitation anomalies are: 1988, 1980, 1983, 1984, and 1991. The precipitation deficits for the 1988 drought was -0.56 MSD that is almost 60% that of the 2012 drought. The precipitation deficits were smaller (-0.5 MSD or less) in other drought events for the Great Plains. It is worth noting that for smaller drought events, the meteorological and agricultural drought can be different, for example in the case of 1983 and 1984, the precipitation anomalies are negative but the soil moisture anomalies are positive in the synthetic observation data (OBS-CLM4.5). While the land-atmosphere coupling improves the ensemble spread to capture the observed anomalies for all these drought years, especially for the soil moisture but the signal

23
strength is not statistically significant. For the 1980 drought, the land-atmosphere uncoupled experiment incorrectly predicts soil moisture drought, but the coupled experiment predicts no drought. The CESM-LE ensemble range capture these drought events, but the signal strengths are not statistically significant.

5.0 Summary and Discussion

We performed a new GLACE-Hydrology Experiment to elucidate the role of the land-atmosphere coupling on the soil moisture variability and drought predictability. A unique contribution of the experiment is the quantitative assessment of the SM-ET coupling difference between the coupled and uncoupled experiments by performing land-only simulations in stage 2. It is worth repeating that the soil moisture and ET were evolving interactively in both the LA-coupled and LA-uncoupled LAND experiments (Stage 2 in Figure 1), but they received different atmospheric forcing: one from the LA-coupled ATM, and another from the LA-uncoupled ATM experiment, respectively (Figure 1). That is, the difference between the two experiments is directly attributable to the climate forcing data. This new result has at least one very important implication: land-atmosphere coupling has a signature that can be detected in land forcing fields. That is, if there are several different land surface models that are forced with the same climate forcing data, then these land surface models may show similar SM-ET correlations. And vice-versa, if the same land surface model is forced with two different climate forcing data, they may show different SM-ET correlations as is the case in this study.

A second contribution of the experiment is highlighting the importance of soil moisture memory that increases soil moisture variability in the mid-latitudes. This is demonstrated in two ways: first using the variance budget analysis (equation 3, and Figures 7 and 9) that clearly show that the memory term is the largest contributor to the increase in soil moisture variability due to
land-atmosphere coupling in the Great Plains region, also in the mid-latitudes, generally. Second, in a specific case of the 2012 Great Plains drought, the memory term contributed to statistically significant improvement in the drought signal.

A robust finding from the GLACE-Hydrology experiment is that the land-atmosphere coupling increases soil moisture memory in the mid-latitude regions and in boreal summer (Figure 6b). A first order effect of the land-atmosphere coupling is a decrease in the moisture (humidity) gradient between the land and the atmosphere. This is generally the case in the mid-latitude and in boreal summer when the evapotranspiration exceed the precipitation, i.e., land acts as a net source of moisture to the atmosphere (Kumar et al. 2014a; Sheffield et al. 2013). Following the Darcy law, the rate of moisture exchange between land and atmosphere will decrease. In other words, the land will keep its moisture for longer duration in soil moisture stores, and therefore land-atmosphere coupling increases the soil moisture memory.

The argument discussed above is similar to the argument presented in a previous study by (Barsugli and Battisti 1998) for ocean-atmosphere thermal coupling in the mid-latitudes. Barsugali and Battisti (1998) found that the coupling between atmosphere and ocean will enhance the temperature variability in both system, and will decrease the energy flux between the ocean and atmosphere in the mid-latitudes oceans. Notwithstanding with the complexities involved in land-atmosphere interaction process, such as limited water availability over land, and as land becomes drier it offers further resistance to moisture flexes (Kumar et al. 2015; Kumar et al. 2013a; Kumar et al. 2016); the simplest null hypothesis of the land-atmosphere coupling is it decreases the moisture exchange between the land and atmosphere, and therefore increases the memory.

We also compared the predictability of the 2012 Great Plains drought from three different sources: land-atmosphere coupling, SST forcing, and climate change. We found that the land-
atmosphere coupled experiment shows statistically significant skill in capturing the 2012 “agricultural drought” despite limited skill in the “meteorological drought” predictions. Improvements in the soil moisture prediction skill is largely due to the soil moisture memory effects (69%) and a smaller contribution from the precipitation anomalies (9%) due to the land-atmosphere coupling. When land-atmosphere coupling was removed, the experiment did not show a statistically significant skill either for the precipitation or for the soil moisture anomalies. For other drought events those were 50% smaller than the 2012 drought, the land-atmosphere coupling generally improved the model performance but the results were not statistically significant.

A multi-model analysis is needed to develop a more comprehensive diagnosis of the role of land-atmosphere coupling in drought predictability. Multi-model data from Land Surface Snow and Soil Moisture Model Inter-comparison Project and Coupled Model Inter-comparison Project Phase 6 – AMIP type experiments can possibly be used (Eyring et al. 2016; van den Hurk et al. 2016). However, these experiments do not include the Hydrology part of the experiment. We are also aware that single forcing large ensemble experiments are currently underway at NCAR and also possibly at few other institutions (Clara Deser, NCAR, personal communication). We hope that this study provides sufficient motivation to include land-atmosphere coupling as a major parameter to better understand predictability of the observed drought events. From our experience, running the hydrology part of the simulation is data intensive (saving the three-hourly data), but the process can be automated if sufficient motivation is found.

Many operational forecasting systems, e.g. Climate Forecast System version 2 and the North American Multi-Model Ensemble seasonal forecasting system include land-atmosphere coupling in their forecast (Kirtman et al. 2014; Saha et al. 2010). However, there are considerable uncertainties in representation of the land-atmosphere coupling and soil moisture memory in the
seasonal forecasting models (Dirmeyer 2013; Dirmeyer and Halder 2017; Dirmeyer et al. 2016; Roundy et al. 2014; Santanello Jr et al. 2015). Recently, the availability of in-situ and remotely sensed soil moisture data (Entekhabi et al. 2014; Quiring et al. 2016) provides the opportunity for improving process level representation of soil hydrology, as well as developing methodology to incorporate observationally constrained soil moisture initial conditions in the seasonal forecast.

Overall, this study demonstrates a new pathway, via soil moisture memory, through which land-atmosphere coupling can impact soil moisture variability and drought predictability. The soil moisture memory pathway acts additionally to the soil moisture and evapotranspiration interactions pathways that have been extensively investigated in previous GLACE studies (Dirmeyer 2011; Guo et al. 2006; Koster et al. 2006). Hence, this study provides new knowledge about the effects of land-atmosphere coupling on land variability.

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Laboratory, sponsored by the National Science Foundation. The experiment data is available upon request to the first author, because data size is too large (20 TB). First author also thanks Yanan Duan (Auburn University) for her help in plotting Figure 12, and A2.
**Figure Captions**

**Figure 1:** Schematic of the GLACE-Hydrology experiment. The left panel shows the generation of atmospheric forcing with land-atmosphere (LA) coupled and LA uncoupled experiments, i.e. the AMIP style run (see text). The right panel shows land-only the LA coupled LAND and LA uncoupled LAND with the respective climate forcing from Step1.

**Figure 2:** Effects of the land-atmosphere coupling on hydroclimate variability. Figure shows the zonal average variance of the temperature, and evapotranspiration in the LA-coupled (blue lines) and LA-uncoupled (red lines) experiments. All 10 × 2 ensemble are shown here. Inter-annual variance are calculated at each grid-cell, then zonal land average are computed, and its squared root quantities are shown. Units are: °C for the temperature, mm/month the evapotranspiration. Gray line in Figure 1(a) shows the GLACE-CMIP5 implementation of the LA-uncoupled ATM experiments. The new scheme in the GLACE-Hydrology experiment significantly improves the temperature variance biases at high-latitudes.

**Figure 3:** Same as Figure 2 for DJF

**Figure 4:** Effects of land-atmosphere coupling on (a) evapotranspiration variability, and (b) precipitation variability. Figure shows the difference between the LA-coupled and LA-uncoupled experiments and for the inter-annual standard deviation quantities averaged over the JJA months. Statistical significance of the difference at 95% level is computed using Monte-Carlo method.

**Figure 5:** Effects of land-atmosphere coupling on soil moisture and evapotranspiration (SM-ET) correlations. Top panel shows the SM-ET correlations in the LA coupled LAND experiment. Its difference from the LA uncoupled LAND experiment are shown in the bottom panel using the
Figure 6: Effects of the land-atmosphere coupling on (a) the soil moisture variability, and (b) the memory. Top panel shows difference between the LA-coupled LAND and LA-uncoupled LAND JJA soil moisture inter-annual standard deviations (unit: mm of water in 3.8m soil column). Bottom panel shows the difference between soil moisture lag1 autocorrelations between two experiments. Statistical significance of the difference at 95% level is computed using Monte-Carlo method.

Figure 7: Decomposition of the total soil moisture variability change by four driver climate processes: (a) the soil moisture memory, (b) the precipitation forcing, (c) the SM-ET coupling, and (d) SM-R coupling in the units of mm/month.

Figure 8: Effects of the land-atmosphere coupling on total runoff variability. Figure shows the difference between the LA-coupled LAND and LA-uncoupled LAND JJA total runoff inter-annual standard deviations (unit: mm of water in 3.8m soil column). Statistical significance of the difference at 95% level is computed using Monte-Carlo method. Unit: mm/month.

Figure 9: Area average contributions of the memory, forcing, SM-ET, and SM-R coupling terms (eq. 3) to the soil moisture variability change due to land-atmosphere coupling in the GLACE-Hydrology experiment. Four regions shown are the Midwest US (MW-US), central-east US (CE-US), central-west Sahel (CW-SH), and central-west India (CW-IND); these regions refer to four boxes shown in Figure 7.
Figure 10: The 2012 drought in climate modeling experiments. Figures shows standardized soil moisture anomalies for JJA season in the respective climate modeling experiment. Statistical significance of the signal (ensemble average) at 95% level is computed using t-test, and respective sample size (10 for LA coup. and LA uncoup. LAND) and 40 for the CESM-LE.

Figure 11: Comparison of the 2012 Great Plains drought predictability in the LA-coupled and LA-uncoupled experiment with the fully coupled large ensemble experiment (CESM-LE), and observations. The LA-coupled and uncoupled experiments uses observed sea surface temperature that follows Atmospheric Model Intercomparision Project protocol. In the CESM-LE experiments, the sea surface temperature is interactively derived from an ocean model. Error bars show 95% range in the respective climate simulations (10 members each for LA coupled and LA uncoupled, and 40 members for CESM-LE). Star sign denotes that the ensemble mean anomalies are significantly different from zero at 95% or greater confidence interval.

Figure 12: Same as figure 11 for five remaining drought years ranked in the order of their precipitation deficit anomalies.

Figure A1: Effects of land-atmosphere coupling on JJA mean soil moisture and precipitation.

Figure A2: Asymmetric response of the land model to the land-atmosphere coupling, i.e. land model responds strongly during dry years compared to wet years. Figure show soil saturation level from LA coupled ATM experiment on the x-axis and lowest level air temperature difference (°C) between the LA coupled ATM and LA uncoupled ATM experiments on y-axis and in four regions: Central North America (CNA), Southern Europe and Eurasia (SEE), Sahel (SAH), and India (IND) for the JJA. These regions are shown in Figure A1. Each data point show the JJA temperature difference and the soil saturation level for the individual grid in the region. Soil saturation level is
from the root zone average (0-1m). The blue thick line shows locally weighted polynomial regression using ‘lowess’ function in R.

Figure A3: Effects of land-atmosphere coupling on 925hpa geopotential height and wind in JJA season.

Figure A4: Wet (P-ET > 0) and Dry regions (P-ET < 0) in the JJA season. Figure show P-ET climatology in units’ mm/month.
Appendix 1: Changes in Mean Climate

We presented extensive discussion on soil moisture variability change and its drivers in the main text. It is worth looking at the changes in the mean climate, and if the changes in mean climate affected the result. A short answer is, the mean climate changed. However, changes in the mean climate did not significantly affect the soil moisture variability through the forcing term (Figures 7 and 9); hence, results in the main text are reasonably independent of the mean climate change.

We will show in this section that soil moisture mean climate change appears to be driven by the circulation change due to land-atmosphere coupling.

Changes in JJA mean Soil Moisture and Precipitation: Figure A1 shows the boreal summer mean soil moisture changes between the LA-coupled and LA-uncoupled LAND experiments. The changes in mean soil moisture are globally extensive and statistically significant and are of both positive and negative signs. The land-atmosphere coupling caused significant drying in the central North America (CAN), Southern Europe and Eurasia (SEE), and Sahel (SAH), and wetting in India (IND). In addition, parts of Congo basin in the central Africa, and northwestern part of the Amazon basin have also become wetter due to land-atmosphere coupling. The soil moisture response follows the precipitation response globally (Figure A1b), with the mid-latitudinal drying in central North America, and Southern Europe and Eurasia, and wetting in the tropics including India, Congo basin, and the southern Amazonia, but excluding the Sahel, which becomes drier. There is also suggestion that the mid-latitude parts of the southern hemisphere e.g. South Africa, Australia, and parts of the La-Plata basin in South America become drier, but these regions have an overall smaller precipitation during JJA season (not shown).

Figure A1(b) also show statistically significant changes in precipitation over the ocean, too. Reader can see global circulation features in the precipitation changes with a general drying
in sub-tropical dry zones including the mid-latitude North Atlantic, and US west coast Pacific Rim. Whereas, the tropical convergence zone shows a wetting response including tropical central Pacific, and India. Drying (negative precipitation change) in the Indian Ocean can be related to the stronger monsoon circulation in which more low level water vapor are transported to the Indian subcontinent from the Indian Ocean. The monsoonal flow then returns southward at high-level troposphere and subsides over the Indian Ocean region e.g. (Wey et al. 2015). In other words, land-atmosphere coupling can induce an intensified summer monsoonal circulation and local Hadley cell.

Why did circulation change due to land-atmosphere coupling? Soil moisture variations affect the surface radiative balance and partitioning into latent and sensible heat fluxes, and thereby increases the variance of surface temperatures compared to the non-interactive experiment (LA uncoupled-ATM) in low to mid-latitude regions (Berg et al. 2014; Delworth and Manabe 1988; Kumar et al. 2010) (Figure 2). Previous studies have also found that land-atmosphere coupling increases mean surface temperature (Berg et al. 2014), that is also supported by regional studies over North America (Teng et al. 2019). But the reason behind the mean temperature change is less understood.

Land responds strongly under the drier condition by increasing the surface temperature, but its response is muted under wet conditions, thereby giving an overall warming signal in JJA mean temperature change (Supplementary Figure 1). Figure A2 shows difference in near surface air temperature between the LA-coupled ATM and LA-uncoupled ATM experiments for each individual year and the grid-cell in the four regions outlined earlier. These differences are plotted against the corresponding soil wetness in the LA coupled ATM experiment. Please note that the soil moisture are same in the LA coupled LAND, and LA coupled ATM experiments. It is evident
that land response is asymmetric to the surface wetness conditions in all four regions. In other word, the land model that responds strongly during dry years by limiting the supply for the evapotranspiration and thereby increasing the surface temperature, but land acts as the receiver of the climate forcing in the wet conditions. This notion is also supported by (Guo and Dirmeyer 2013) who found inter-annual variability land-atmosphere coupling are modulated due to surface wetness conditions.

An increased surface temperature affect surface pressure anomalies between land and ocean and thereby induces circulation anomalies that propagate into upper atmospheric levels e.g. (Koster et al. 2016; Teng et al. 2019). Figure A3 shows geopotential heights and wind at 925hpa. A negative anomalous 925 hpa geopotential heights corresponding to the lower surface pressure for most of continental areas, while there are positive anomalies over the northern Pacific and Northern Atlantic oceans. Miyasake and Nakamura (2005) used the numerical model to demonstrate the critical role of land-sea thermal contrast for the formation and maintenance of the northern hemisphere summertime subtropical highs, as also suggested by Wu and Liu (2003) and Liu et al. (2004), Seager et al. (2003). Thus, the stronger subtropical high over the Atlantic and Pacific oceans can be related to the enhancement of near-surface thermal contrasts in the eastern ocean owing more warming over the land due to land-atmosphere coupling. Besides, the tropical convections move northward in the summer; thus lead to stronger subsidence and cause stronger subtropical high.

Figure A4 shows climatological P-ET analysis in the LA coupled ATM experiment and for boreal summer season. P-ET map is an indicator of the net moisture convergence represented by a positive P-ET, and net moisture divergence for negative P-ET. Both, CNA and SEE regions are net moisture divergence regions during the boreal summer, and both regions become further drier.
due to land-atmosphere coupling (Figure A1). India is a net moisture convergence region which becomes wetter due to land-atmosphere coupling. A similar response is also seen over the North Atlantic and Pacific sub-tropical dry zones (negative P-ET), where drying enhances at the edges of the deep dry zones. Sahel represents a diverging region towards its northern boundary, and converging region towards the southern boundary, and shows an overall drying response (Figure A1). Thus, a first order response of the land-atmosphere coupling is consistent with the ‘wet-gets-wetter and dry-gets-drier’ paradigm in the summer hemisphere (Held and Soden 2006; Kumar et al. 2015). There are exception in the winter hemisphere e.g. southern Amazonia in South America, and central Congo basin in Africa. Overall, we conclude that the circulation changes derives the mean precipitation changes that affected the mean soil moisture climate (Figure A1).
References


Hoell, A., and Coauthors, 2016: Does El Nino intensity matter for California precipitation?


temperature and sea ice boundary dataset for the Community Atmosphere Model. *J
Climate*, 21, 5145-5153.


initialized CCSM4 climate forecasts over North America. *Journal of Geophysical
Research: Atmospheres*, 121, 12,690-612,701.

States (1901-2012): The influence of the Pacific and Atlantic Oceans. *Geophysical
Research Letters*, 41, 5897-5903.

Kay, J. E., and Coauthors, 2015: The Community Earth System Model (Cesm) Large Ensemble
Project a Community Resource for Studying Climate Change in the Presence of Internal

Kirtman, B. P., and Coauthors, 2014: THE NORTH AMERICAN MULTIMODEL ENSEMBLE
Phase-1 Seasonal-to-Interannual Prediction; Phase-2 toward Developing Intraseasonal


predictability of long-term drought and pluvial conditions in the US Great Plains. *J Climate*, 21, 802-816.

Understanding with a Focus on SST Drivers of Precipitation Deficits. *J Climate*, 29, 3989-4019.


Table 1: The GLACE-Hydrology Experiment details and its comparison with other experiments.

<table>
<thead>
<tr>
<th>Exp. Type</th>
<th>Experiment ID</th>
<th>Soil Moisture</th>
<th>Climate Forcing</th>
<th>SST Forcing</th>
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<td>Interactive</td>
<td>Time evolving observed (Hurrell et al., 2008)</td>
<td>Kay et al., 2015</td>
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<td></td>
<td>CRUNCEP V2</td>
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Variables Analyzed:
- Precipitation
- Evapotranspiration
- Soil moisture
- Temperature
Figure 1: Schematic of the GLACE-Hydrology experiment. The left panel shows the generation of atmospheric forcing with land-atmosphere (LA) coupled and LA uncoupled experiments, i.e. the AMIP style run (see text). The right panel shows land-only the LA coupled LAND and LA uncoupled LAND with the respective climate forcing from Step1.

**Step 1:** Generate atmospheric forcing data under LA coupled and uncoupled scenarios using AMIP style run

**Step 2:** Run offline land/hydrology model simulations using atmospheric forcing from Step 1.
Figure 2: Effects of the land-atmosphere coupling on hydroclimate variability. Figure shows the zonal average variance of the temperature, and evapotranspiration in the LA-coupled (blue lines) and LA-uncoupled (red lines) experiments. All $10 \times 2$ ensemble are shown here. Inter-annual variance are calculated at each grid-cell, then zonal land average are computed, and its squared root quantities are shown. Units are: °C for the temperature, mm/month the evapotranspiration. Gray line in Figure 1(a) shows the GLACE-CMIP5 implementation of the LA-uncoupled ATM experiments. The new scheme in the GLACE-Hydrology experiment significantly improves the temperature variance biases at high-latitudes.
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Figure 5: Effects of land-atmosphere coupling on soil moisture and evapotranspiration (SM-ET) correlations. Top panel shows the SM-ET correlations in the LA coupled LAND experiment. Its difference from the LA uncoupled LAND experiment are shown in the bottom panel using the dimensional unit. Statistical significance of the difference at 95% level is computed using Monte-Carlo method.
Figure 6: Effects of the land-atmosphere coupling on (a) the soil moisture variability, and (b) the memory. Top panel shows difference between the LA-coupled LAND and LA-uncoupled LAND JJA soil moisture inter-annual standard deviations (unit: mm of water in 3.8m soil column). Bottom panel show the difference between soil moisture lag1 autocorrelations between two experiments. Statistical significance of the difference at 95% level is computed using Monte-Carlo method.
Figure 7: Decomposition of the total soil moisture variability change by four driver climate processes: (a) the soil moisture memory, (b) the precipitation forcing, (c) the SM-ET coupling, and (d) SM-R coupling in the units of mm/month.
Figure 8: Effects of the land-atmosphere coupling on total runoff variability. Figure shows the difference between the LA-coupled LAND and LA-uncoupled LAND JJA total runoff inter-annual standard deviations (unit: mm of water in 3.8m soil column). Statistical significance of the difference at 95% level is computed using Monte-Carlo method. Unit: mm/month
Figure 9: Area average contributions of the memory, forcing, SM-ET, and SM-R coupling terms (eq. 3) to the soil moisture variability change due to land-atmosphere coupling in the GLACE-Hydrology experiment. Four region shown are the Midwest US (MW-US), central-east US (CE-US), central-west Sahel (CW-SH), and central-west India (CW-IND); these regions refer to four boxes shown in Figure 7.
Figure 10: The 2012 drought in climate modeling experiments. Figures shows standardized soil moisture anomalies for JJA season in the respective climate modeling experiment. Statistical significance of the signal (ensemble average) at 95% level is computed using t-test, and respective sample size (10 for LA coup. and LA uncoup. LAND) and 40 for the CESM-LE.
Figure 11: Comparison of the 2012 Great Plains drought predictability in the LA-coupled and LA-uncoupled experiment with the fully coupled large ensemble experiment (CESM-LE), and observations. The LA-coupled and uncoupled experiments uses observed sea surface temperature that follows Atmospheric Model Intercomparison Project protocol. In the CESM-LE experiments, the sea surface temperature is interactively derived from an ocean model. Error bars show 95% range in the respective climate simulations (10 members each for LA coupled and LA uncoupled,
and 40 members for CESM-LE). Star sign denotes that the ensemble mean anomalies are significantly different from zero at 95% or greater confidence interval.
Precipitation droughts in the Great Plains and the corresponding soil moisture droughts/no drought in the order of their precipitation deficit anomalies.
Figure A1: Effects of land-atmosphere coupling on JJA mean soil moisture and precipitation.
Figure A2: Asymmetric response of the land model to the land-atmosphere coupling, i.e. land model responds strongly during dry years compared to wet years. Figure show soil saturation level from LA coupled ATM experiment on the x-axis and lowest level air temperature difference (°C) between the LA coupled ATM and LA uncoupled ATM experiments on y-axis and in four regions: Central North America (CNA), Southern Europe and Eurasia (SEE), Sahel (SAH), and India (IND) for the JJA. These regions are shown in Figure A1. Each data point show the JJA temperature difference and the soil saturation level for the individual grid in the region. Soil saturation level is from the root zone average (0-1m). The blue thick line shows locally weighted polynomial regression using ‘lowess’ function in R.
Figure A3: Effects of land-atmosphere coupling on 925hpa geopotential height and wind in JJA season.
Figure A4: Wet (P-ET > 0) and Dry regions (P-ET < 0) in the JJA season. Figure show P-ET climatology in units’ mm/month.