

Land-atmosphere interactions in monsoon regimes and future prospects for enhancing prediction

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Introduction

Monsoons are annual large-scale phenomena that form an integral part of global-scale circulations. Monsoon circulations are driven and maintained by seasonal contrasts in the thermal heating of land and sea. Beginning in spring, the land warms. Sensible and latent heat are released from the land surface into the atmosphere, driving the formation of low pressure that induces air flow from the ocean. The heating in the land triggers convection, producing clouds and generating rain. The monsoon flow is intensified by convective uplift as well as topographic forcing where mountains exist. These forcings and thermal gradients influence the strength, duration, and spatial distribution of large-scale monsoon systems (e.g., Dirmeyer, 1998; Webster et al., 1998; Xue et al., 2004). Therefore, land/atmosphere interaction plays a crucial role in monsoon systems by their very nature.

Monsoons exhibit substantial seasonal, interannual, and decadal variability that results in severe droughts, such as the most significant West African drought in the last century (e.g., Xue et al., 2010a), and floods such as those occurred recently in central China (Ding et al., 2008). Land surface processes may play an important role in these extreme events through modulating the heat gradient and moisture supply (e.g., Xue and Shukla, 1993; Xue, 1996). Despite the importance of the monsoonal systems in providing water for agriculture in many of the world's most populous regions, the effect of land/atmosphere interactions in the monsoon system is still poorly understood. Figure 1 shows the sources of moisture supplying rainfall over the major monsoon systems of the world (Dirmeyer et al. 2014), estimated using a water vapor back-trajectory analysis algorithm (cf. Dirmeyer and Brubaker 2007). The classical monsoon circulation features are evident, bringing oceanic moisture inland, but within those circulations a great deal of the rainfall comes from moisture recycled over land from terrestrial evaporation. These land surface fluxes provide a means for land-atmosphere interactions to modulate the monsoons, as further described below.

Identification of the role of land in the monsoon system

It has been shown that land surface processes have considerable influence over the monsoon regions. The Global Land–Atmosphere Coupling Experiment (GLACE: Koster et al., 2004; 2006; Guo et al. 2006) investigated soil moisture/atmosphere coupling strength across the globe during boreal summer with multiple general circulation models (GCMs). Figure 2a shows estimates averaged across twelve of the participating models, with higher values implying a higher control on precipitation anomalies by the soil moisture conditions. This multi-model estimation of land atmosphere coupling strength reveals that monsoon regions, such as the Sahel and South Asia, have some of the strongest soil moisture/climate couplings in the world. This has been borne out in regional modeling studies over specific monsoon regions (e.g., Steiner et al. 2009; Saha et al. 2011; 2012).

The mechanism identified in GLACE favors strong land-atmosphere interactions in transition regions between arid and humid regimes (Dirmeyer et al. 2009). In dry locations with abundant radiative energy there is a strong control on surface fluxes by soil moisture; its availability increases latent heat flux and its absence results in net radiation going into sensible heat flux. However, in arid regions the dry atmosphere is unresponsive to small additions of moisture. On the other hand, in warm humid regions the atmosphere is often near moist convective instability, and the addition of additional moisture to the atmospheric profile can decrease stability, increase clouds and convection. However, fluxes at the land surface, especially when modulated by vegetation as discussed below, are insensitive to variations in soil moisture unless the soil becomes very dry. Only in the regions between arid and humid does one find a degree of sensitivity in both the land surface and atmosphere, so that the feedback loop is complete.

In addition to soil moisture, the land surface has other avenues of interaction with the atmosphere. These processes include radiative transfer in the canopy and the associated radiation balance at the surface, transpiration by vegetation due to stomatal control and its connection to root water uptake, canopy interception loss, and variations in aerodynamic resistances of momentum and heat due to vegetation morphology and land use practices. We refer to this collection as biogeophysical processes (BGP). The impact of BGP on the climate system has been investigated using the GCMs coupled to different benchmark land parameterizations with varying degrees of physically-based complexity in their representation of BGP (Xue et al., 2004b, 2006, 2010b): one land model has fully interactive BGP/atmosphere interaction (but no dynamic vegetation); another consists of only two-way direct soil moisture interaction with the atmosphere but no vegetation, and a third has specified soil moisture and other land attributes, such as albedo and roughness length. The importance of BGP effects on climate were assessed based on the skill of simulations of observed variables by GCMs with different land benchmark models. The statistically significant reduction of errors between simulated variables and the observation was adopted as the criteria to identify BGP effects. Observational and reanalysis data were used for the applications of these criteria. Figure 2b shows the reduced absolute mean bias of 5-year summer precipitation simulations (or improved prediction skill) with this approach due to inclusion of BGP process in the GCM (Xue et al., 2010b). Figures 2a and 2b, from two entirely different approaches, show consistency in identifying the West African and South Asian monsoon regions as hot-spots of land/atmosphere interaction. Meanwhile, the second approach has identified more regions including some in the Southern Hemisphere because Figure 2a only includes boreal summer effects. Figure 2c shows regional average BGP/atmosphere coupling strength in different

seasons (Xue et al., 2010b). BGP has the greatest impact on monsoon regions during the local summer and the local fall.

The controls of the land surface on the atmosphere described above are all in terms of positive feedbacks through the water cycle. There are also regimes of negative water cycle feedbacks that are relevant to monsoons, particularly on the dry margins of monsoon systems like the Sahel, the southwestern United States, Northwest India and Pakistan (Ferguson and Wood, 2011; Ferguson et al. 2012; Taylor et al. 2012). In such locations a dry soil advantage for cloud formation and convection can exist where deeper boundary layers driven by extra sensible heating are more advantageous than additional moistening by latent heat flux (Findell and Eltahir 2003).

Land use and land cover change (LULCC) and monsoons

The impact of LULCC has been extensively investigated in land/monsoon interaction studies, which along with the soil moisture studies are among the two most investigated subjects in land/atmosphere interaction research.

The South American monsoon system is unique in that its main source of moisture is largely terrestrial rather than oceanic, coming from over the rainforests of the Amazon (Fig 1). The Amazon Basin contains the largest extent of tropical forest on Earth and the rapid expansion of agriculture and timber harvest since the 1950s has led to large-scale deforestation (Nobre et al., 2004). Many studies with GCMs and regional climate models (RCMs) have investigated the impact of tropical deforestation on the regional and global climate (e.g., Dickinson and Henderson-Sellers 1988; Nobre et al. 1991; Polcher and Laval 1994; Sud et al., 1996; Xue et al., 1996; Samapio et al., 2007; Correia et al., 2008). Almost all models produce higher surface temperature and lower evaporation over the deforested areas. Field experiments such as the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) have been conducted to support such research (Nobre et al., 2004). However, these studies disagree on the impact of deforestation on precipitation, as most modeling studies have indicated patterns of both decreasing and increasing rainfall along with shifting seasonal changes. Since the South American monsoon was first identified (Zhou and Law, 1998) studies have explored BGP process effects on the South American monsoon development (e.g., Xue et al., 2006), but no studies have specifically focused on the LULCC impact on this monsoon system.

LULCC in the West African monsoon system has been the subject of much investigation. Since Charney's first study (1975) on albedo and North African drought, this subject has been surrounded by controversy over the role of land degradation, its extent and consequences on Sahelian drought. For instance, satellite evidence (Nicholson et al., 1998) shows that albedo change in West Africa has been less than that required by the radiatively-driven hypothesis for drought in the Charney et al. (1997) study. Their proposed cooling with higher surface albedo was inconsistent with the general warming associated with surface roughness changes accompanying land degradation (Ripley, 1996). Furthermore, it has been found that in the Northern Hemisphere descent regions of the Hadley circulation, the time-mean horizontal advection term was twice as strong as the time-mean diabatic-cooling term that the albedo effect would produce (Rodwell and Hoskins, 1996).

Therefore, more realistic BGP-based land-surface models are needed to assess realistically the impact of desertification on the Sahel drought. A proper evaluation of the surface feedback to climate can be obtained only when all comparable components

of the energy and water balances are considered. In the coupled GCM/BGP model, it was found that after a dramatic vegetation reduction, land degradation could lead to regional monsoon climate changes of the order of the differences found between the 1980s (a severe drought period) and the 1950s (a very wet period), with warming and reductions in the summer monsoon rainfall, runoff, and soil moisture over the Sahel region. The impact is not limited to the specified desertification areas but it also south of this area due to modifications in the circulation (Xue and Shukla, 1993; Xue, 1997; Xue et al., 2004).

Furthermore, despite the consensus that the sea surface temperature (SST) may play a major role in the West African drought, the Climate of the 20th Century international project (C20C; Kinter and Folland 2011) with multiple state-of-the-art GCMs forced by observed SSTs found most models failed to produce observed droughts while two models simulated only half the magnitude of the Sahel monsoon rainfall changes between the 1980s and the 1950s. Scaife et al. (2008) conclude that the Sahel drought is only partly forced by SST anomalies. To achieve a better understanding of the external forcing on the West African monsoon decadal variability, the West African Monsoon Modeling Experiment (WAMME) has been designed to use multiple GCMs and RCMs to elucidate the relative roles of SST, LULCC, and aerosols in West African monsoon variability (Xue et al., 2010a; Boone et al., 2010).

The effect of LULC changes on South Asian and East Asian monsoons and global climate have also been studied (e.g., Dirmeyer and Shukla, 1996; Xue, 1996; Fu et al., 2003; Takata et al., 2009; Li and Xue, 2010; Niyogi et al., 2010; Mahmood et al., 2004). A companion to agriculture in semi-arid regions is increased irrigation, and several studies have suggested the recent expansion of irrigation in Northwest India and Pakistan could be having deleterious effects on monsoon precipitation (Douglas et al. 2009; Saeed et al. 2009; Tuinenberg et al. 2012; Guimberteau et al. 2012; Wei et al. 2013). With more LULCC data available from different sources showing substantial LULCC in past decades (e.g., Hurtt et al., 2006; Kim et al., 2014) and experience gained from the previous multi-model studies (e.g., Pitman et al., 2009), LULCC effects in the monsoon system can be more realistically assessed.

Future Perspectives

The relationship between changes in the slowly varying boundary conditions at the earth's surface (e.g., SST and BGP) and changes in atmospheric circulation and rainfall are the focus of much research. More comprehensive investigation is required; realistic simulation of monsoons and better understanding of its processes remain a formidable task. In the recent CLIVAR land-monsoon initiative, several key issues were identified for further investigation: land/atmosphere feedbacks (vegetation, dust), short time-scale tie-ins with intra-seasonal variability work, longer timescale efforts to understand the impact of different model land use treatments and inter-model differences, and identifying where and when hotspots of land-atmosphere coupling occur. Multi-model experiments with carefully selected and benchmarked land parameterizations and adequate diagnostic metrics (with the associated data required) are necessary to diagnose monsoon land-surface interactions more completely.

Dynamic vegetation models have been developed for two-way land/monsoon interaction studies, such as the West African Sahelian drought study (Zeng et al., 1999; Wang and Eltahir, 1999). Although such models are still at the preliminary stage, several studies with the West African monsoon as a prime subject have demonstrated their promising potential.

The study by Zeng et al. (1999) illustrated how the combination of multiple feedbacks, each with its own time constant, recreates realistic rainfall variability. Especially when a drought is persistent, the ecosystems themselves may migrate. However, recent CMIP5 results have revealed that these models exhibit significant deficiencies in decadal climate simulations (Murray-Tortarolo et al., 2013). Proper model evaluations with observational data are necessary to employ dynamic vegetation models for the land/monsoon interaction studies.

GLACE-2 (Koster et al. 2010; 2011) demonstrated that improved prediction skill can be achieved by realistic land surface initialization. However, realistic land initialization is not sufficient if the model climate is unrealistic, i.e., if there exists strong climate drift in the model. The role of model biases in the atmosphere as well as land as a limit to our predictive capability needs to be evaluated. The quality of land surface initialization also depends on the quality of forcing data for land surface analyses, particularly precipitation (Oki et al. 1999; Koster et al. 2011), but operational monitoring of precipitation is lacking in many monsoon areas and needs to be improved. Monitoring of surface fluxes, boundary layer development and soil moisture in monsoon regions would also help advance process-level understanding of land-atmosphere interactions in these regimes. These efforts would put us in a better position to advance monsoon research, particularly for the purposes of prediction.

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Figures :

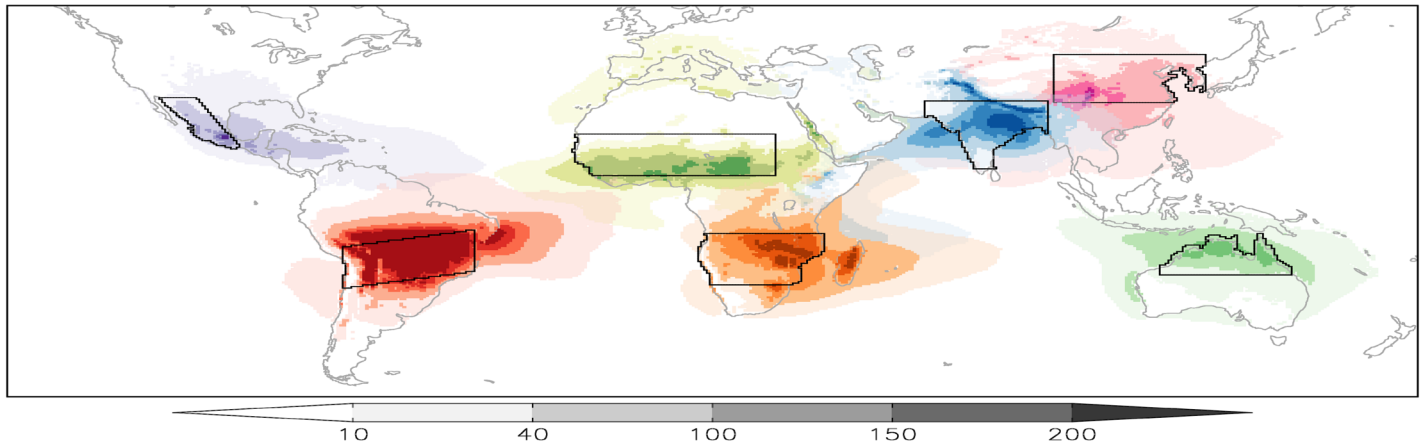


Figure1: Evaporative source (kg m^{-2}) supplying rainfall over the outlined monsoon regions during July-August in the Northern Hemisphere, January-February for Southern Hemisphere, derived from the quasi-isentropic back trajectory data set of Dirmeyer et al., (2014) for 1979-2006. Levels of shading for each color follow the grey scale at the bottom

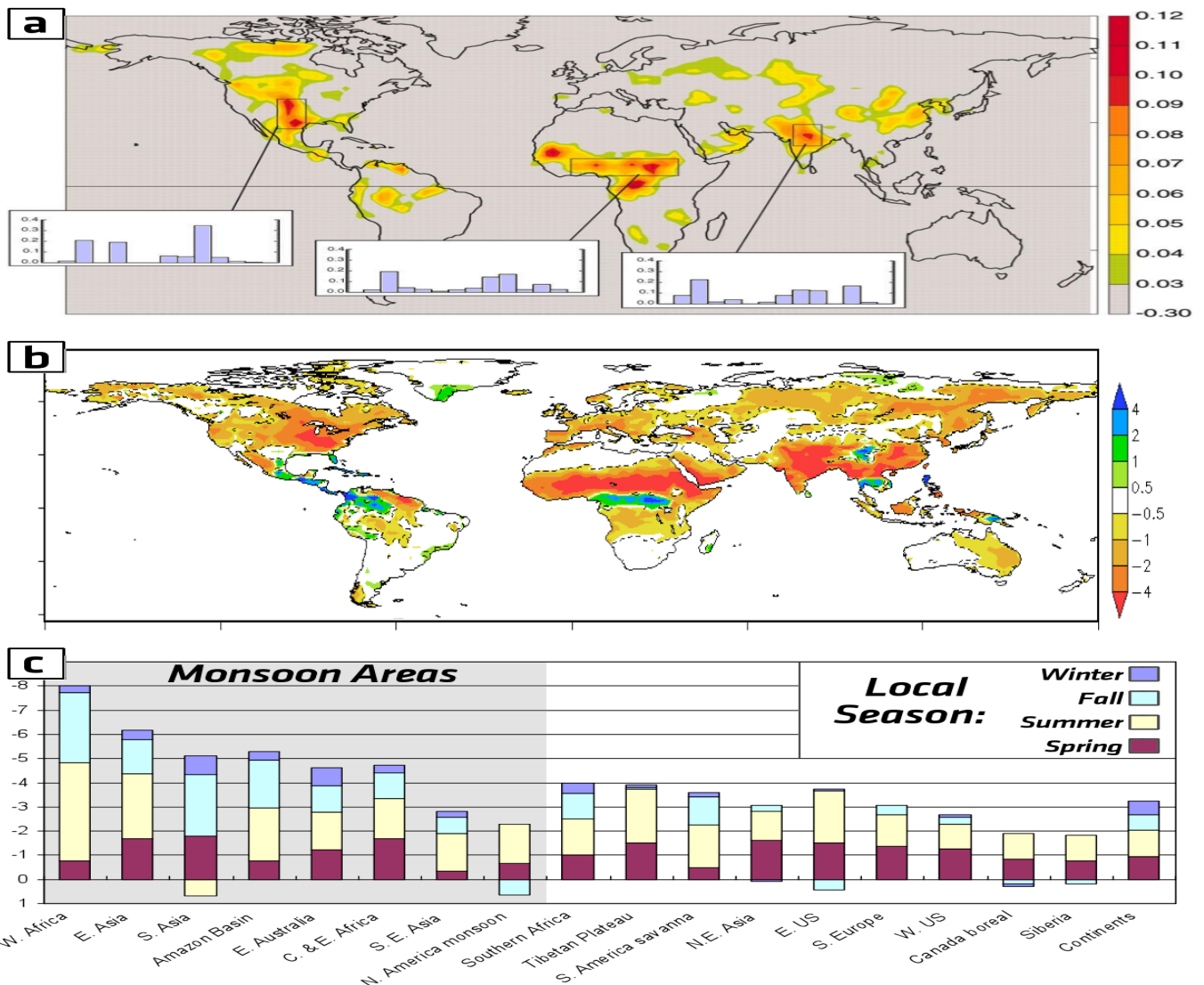


Figure 2: a) Hot spots of land-atmosphere coupling from the multi-model GLACE experiment (dimensionless; reproduced from Koster et al. 2004); b) change in local summer precipitation bias (mm d^{-1}) due to inclusion of land surface BGP processes in a single climate model (Xue et al., 2010b); c) average BGP/atmosphere coupling strength in different seasons (mm d^{-1}) from Xue et al. (2010b) with monsoon regions highlighted.