Land surface processes and monsoon

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Abstract

This paper presents the possible impact of vegetation processes on East Asian and South American monsoon development. Difficulty and challenge in study of land surface/monsoon interactions are discussed. Case studies are presented to show how vegetation process affects intraseasonal monsoon variability. We compare simulations by a NCEP GCM coupled with two different land surface parameterizations, a two-layer soil model with no explicit vegetation representation, and a more comprehensive biophysical model. It was found that vegetation-induced heating produced large scale air flow tuning at the monsoon onset stage in East Asia, Africa, and South America, which affected the extent and intensity of the monsoon onset. It also found that in the East Asian monsoon season, vegetation processes produce different spatial distributions of the Bowen Ratio, in turn influencing the low-level temperature and pressure gradients, wind flow (through geostrophic balance), and moisture transport. This process creates the great east-west thermal gradient, which may contribute to the abrupt northward jump of the East Asian monsoon. In South America, the seasonal varied sensible heating in Savanna and Shrub lands produced anticyclone system, which prevented the early monsoon onset in October and early monsoon merge with ITCZ in December, which is the beginning of the monsoon mature stage. The different characteristics of land/monsoon interaction in East Asian, African, and South American continents were also addressed. By and large, the results show that feedbacks between vegetation and the atmosphere are crucially important for proper simulation of intra-seasonal monsoon evolution, including its intensity, the spatial distribution of precipitation, and associated circulation at the continental scale, but not at planetary scale (after excluding albedo and initial soil moisture).

Key words: Monsoon, vegetation, East Asia, South America, GCM

1. Introduction

Differential heating of the land and the ocean has greatly influenced the strength, duration, and spatial distribution of large-scale monsoons. The land surface processes are crucial in modulating the monsoon processes. Although several GCM studies (i.e., Xue and Shukla, 1994; Meehl, 1994; Lau and Bua 1998; Dirmeyer, 2000; Xue et al., 2004; Koster, et al., 2004), which explore potential role of land surface processes in hydrometeorological predictability, have consistently shown that soil moisture and vegetation cover have the great impact on the climate in monsoon regions, but role in intraseasonal monsoon variability is poorly understood, as is the role of parameterizations of land surface processes in seasonal prediction. Furthermore, different models exhibit very different sensitivity to the land surface forcing (Koster et al., 2004). These difference may be rooted in the ways that, for example, they treat the surface water and energy balances in their models, they parameterize the vegetation/soil processes, they couple with atmospheric model, especially the PBL and cloud processes, or the data that they use to specify the land surface condition.

Case studies are presented to show how vegetation process affects intraseasonal monsoon variability (Xue et al., 2004a, 2004b). We compare simulations by using a NCEP GCM coupled with two different land surface parameterizations, a two-layer soil model with no explicit vegetation representation, and a more comprehensive biophysical model. The results show that feedbacks between vegetation and the atmosphere are crucially important for proper simulations of intra-seasonal monsoon evolution, including its intensity, the spatial distribution of precipitation, and associated circulation at the continental scale.

2. East Asian study

Results of our general circulation model investigation suggest that vegetation processes produce different spatial distributions of the Bowen Ratio (sensible versus latent heating), in turn influencing the low-level temperature and pressure gradients, wind flow (through geostrophic balance), and moisture transport. This process causes the latitudinal heating gradient that contributes to the clockwise and counterclockwise turning of the low-level wind on the East Asian, African, and American continents during the early stages of the monsoon development. For example, vegetation processes produced relative lower pressure to the south and relative higher pressure to the north in East Asia. An anomalous eastward wind with vegetation processes would be produced while Coriolis forcing balanced the pressure gradient force based on geostrophic balance. This turning would affect the extent and intensity of the monsoon onset. In the monsoon mature stage, when the convective heating is dominant, with and without vegetation heating make no substantial differences.

In the East Asian study, the role of land surface processes in the abrupt monsoon northward jump was explored. The abrupt northward jump of the East Asian monsoon has been described by numerous studies but it has not been simulated before and its cause is still unclear. It was found that the simulation with/without vegetation processes had large differences in northward low-level moisture transport. In the late part of June, the moist region and meridional wind in the simulations with vegetation processes had a dramatic northward expansion between 25°N and 40°N, which was consistent with the timing of the northward jump of the precipitation band and provided the necessary moisture. Without vegetation, on the other hand, the simulation did not show such dramatic northward expansion. The maximum humidity and meridional wind were confined to the south of the Changjiang River. Since northward transport of the water vapor was the main moisture source of the East Asian summer monsoon. The differences that discussed above would have great impact on monsoon development. The surface energy balances were analyzed to understand the mechanisms that produced these differences. It was found that the differences in radiative heating and latent heat flux were not large between the simulations with/without vegetation. The major differences were in the sensible heat flux. Based on the geostrophic balance in mid-latitude, the northward wind should be produced by the east-west pressure gradient. Among surface upward heating components, only sensible heat fluxes in the simulation with vegetation processes exhibited a clear east-west gradient. Based on these analyses and previous theoretical studies, we suggest that the greater east-west thermal gradient, which produced strong northward transport of moisture and a cyclone condition, may contribute to the abrupt northward jump of the monsoon.

3. South American study

In the South American case, the impact of land surface processes on the South American monsoon system (SAMS) onset and evolution are also investigated. SAMS is the second largest monsoon in the world. The evolution of the SAMS starts during the austral spring as intense convection around the equator. This then moves southeastward towards the Amazon, where the monsoon regime establishes itself in the austral summer. The location of maximum precipitation is furthest southeast from September to December and then moves back northeastward from the subtropics and eventually returns to the tropics and merge with the ITCZ in the monsoon mature stage. The dry and wet seasons were present in the simulations without vegetation processes, but some important features of the SAMS evolution were missed. First, the southeastward evolution of the precipitation from September to December was diffuse. The monthly mean values showed a brief southward movement in September followed by a uniform northwest-southeast precipitation band that extended from 5˚N to 25˚S in October and then a strong northward movement, which caused an early merge with ITCZ in December, producing a very wet monsoon season. The dry area near the equator did not appear in this period. On the other hand, simulations with vegetation processes correctly simulated the SAMS southward movement in the austral spring. The maximum monthly mean precipitation in October was correctly located in the Amazon and then gradually moved southeastward. Furthermore, the northward movement started after December and merged with ITCZ in the SAMS mature stage, consistent with the major observed features of the SAMS evolution processes.

To understand the mechanisms, which cause these differences, surface energy budget has been analyzed. It was found that the most substantial differences were in the partitioning between latent and sensible heat fluxes such that simulations with vegetation processes persistently produced lower latent heat flux and higher sensible heat flux. Furthermore, these differences exhibited high temporal and spatial variability, with maximum changes in sensible heat flux being occurred during October - January. The analysis revealed that the seasonality of savanna in southeast Brazil and shrubs in northeast Brazil played crucial role in reduction in evaporation and increase in sensible heat flux in simulations. These produced an anticyclone system and divergence, which in turn prevented early monsoon development and early merge of SAMS with ITCZ.

4. Discussion and summary

The results discussed above show very different mechanisms in land/atmosphere interactions in different continents. In East Asia, the differences in latent heat fluxes between the simulations with/without vegetation were much smaller than sensible heat fluxes. The differences in precipitation generally correlated with the changes in moisture flux. The influence of surface processes on monsoon was mainly manifested in its impact on the large-scale circulation. In Africa, in June during the monsoon onset, although the evaporation reduction in some areas in Africa may have contributed to the precipitation decrease, the major rainfall change in the Sahel was consistent with the changes in moisture flux. In August, the monsoon mature stage, the effect of evaporation prevailed and contributed to the large rainfall changes in the Sahel, consistent with Xue (1997). Compared with the East Asia, land-surface evaporation played a more important role in the variation of West African monsoon. In South America, the evaporation was very dominant. It provided almost all the moisture sources for the precipitation differences between the simulations with and without vegetation processes. But the precipitation anomalies were generally consistent with the moisture flux convergence, which is closely associated with sensible heat flux.

Our modeling results show that under unstable atmospheric conditions, the evolution of the monsoon's intensity, the spatial distribution of precipitation, and associated continental-scale circulation are affected by the perturbation processes of vegetation, not just by low frequency mean land surface forcings such as monthly mean albedo. We coupled a general circulation model with two different land-surface parameterizations, with and without explicit vegetation representations. A number of simulations used these two models but with the same initial soil moisture and monthly mean surface albedo. Thus, the main differences between these two models are short-term vegetation forcings, such as radiative flux/canopy interaction and transpiration. By comparing the results from these two models, we can identify the effect of vegetation and mechanisms of land/atmosphere interaction.

However, these studies are based on a single GCM model and a specific year. Recent studies with different models show that different GCM coupled with different land models exhibit very different sensitivity to the land surface forcing (Koster et al., 2004). Proper simulations of land/monsoon interaction are challenge and difficulty. The factors and issues related to modeling land/atmosphere interactions need be further explored. In addition, the effects of different land processes, such as land cover change and soil moisture, in intra-seasonal variability also need to be further explored.

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