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How land surface heterogeneity impacts on energy partitioning and atmospheric boundary development

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Abstract: The land surface is heterogeneous with respect to, for example, land use, plant cover, soil moisture, and topography over a wide range of spatial scales, which strongly influences the integrated energy and water budgets at the land surface and in the atmosphere. Soil moisture constitutes a key factor in the land surface and atmosphere coupled system regulating atmospheric states on time-scales ranging from the diurnal cycle to seasonal variations by affecting surface temperature, partitioning of surface net radiation, and inducing microscale to mesoscale circulations, which influence the development of the daytime convective planetary boundary layer (CBL), and thus, the initiation and intensity of convective clouds and precipitation.

The impacts of soil moisture heterogeneity on the development of catchment-scale circulations (CCs) and the atmospheric boundary layer were studied applying large-eddy simulations (LESs). A continuous river-like soil moisture pattern, rather than discrete patch-like soil moisture pattern, was used to avoid unrealistic abrupt variation of the surface variables. A series of eight simulations with heterogeneous soil moisture were performed with horizontal valley widths ranging from 0.6 to 76.8 km, with the same 50 m horizontal grid spacing in each horizontal direction. In this way, the domain mean soil moisture values are maintained.

The simulation results show that the intensity of organized circulations resulting from soil moisture heterogeneity is nonlinearly dependent upon soil moisture heterogeneity scale λ (SMHS) and horizontal gradient. Because of the large SMHS and strong soil moisture contrast, none of the simulations has reached a true steady state even after 24 h of simulation time. The intensity of organized circulations shows a sigmoidal dependence on SMHS. The optimal SMHS for horizontal transport is on the order of 19.2 km, while optimal SMHS for vertical motions occurs at 2.4 km. In these cases, the CCs also exert a strong influence on the boundary-layer structure and the entrainment layer. The potential temperature is not constant with height due to a weak mixing in the boundary layer for large SMHS cases. Differences in sensible heat flux profiles between the heterogeneous cases increase with increasing height and reach a maximum at the top of the CBL. Interestingly, boundary-layer height changes strongly with changing horizontal soil moisture gradient and SMHS while domain means, variances, and amplitudes of land surface energy fluxes are all almost identical. The entrainment flux and subsidence at the top of the CBL are jointly responsible for the CBL height variation.

To mimic a more realistic soil moisture distribution, two-dimensional soil moisture heterogeneities were generated applying spatially correlated Gaussian fields based on a power law model. Three sets of LESs, with prescribed strong, weak, and unstructured soil moisture heterogeneity, were performed to investigate the influence of soil moisture heterogeneity on the ensuing growth of the convective boundary layer and development of shallow cumulus clouds.

The simulation results show that domain-averaged land surface sensible heat and latent heat flux change strongly with changing soil moisture variance because of the interactions between surface heterogeneity and induced circulations, while domain means of soil moisture are identical. Vertical profiles of boundary layer characteristics are strongly influenced by the surface energy partitioning and induced circulations, especially the profiles of liquid water and liquid water flux. The amount of liquid water and liquid water flux increases with increasing structure. In addition, the liquid water path is higher in case of strong-structured heterogeneity because more available energy is partitioned into latent heat and more intensive updrafts exist. Interestingly, the increase of liquid water path with increasing soil moisture variance only occurs in the strongly structured cases, which suggests that soil moisture variance and structure work conjunctively in the surface energy partitioning and the cloud formation.

Keywords: *Soil moisture heterogeneity, mesoscale circulation, convective boundary layer*