Assessing the uncertainty of soil moisture impacts on convective precipitation using a new ensemble approach

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Abstract. Soil moisture amount and distribution controls evapotranspiration and thus impacts the occurrence of convective precipitation. ~~Many~~ recent model studies have ~~proved this interaction and~~ demonstrated that changes in initial soil moisture condition result in modified convective precipitation. At the same time, the chaotic behavior of the atmospheric system needs to be considered: any slight changes in the simulation setup, such as the chosen model domain, also result in modifications in the simulated precipitation field. This uncertainty caused by ~~the~~ stochastic variability is large compared to soil moisture effects as we will show. By shifting the model domain, an estimate on the uncertainty of the model results can be calculated. This uncertainty estimate, which includes ten simulations with shifted model boundaries, is compared to the effects on precipitation, ~~which are caused by~~ variations in soil moisture amount and local distribution. With this approach, the influence of soil moisture amount and distribution on convective precipitation is quantified. Deviations in simulated precipitation can only be attributed to soil moisture impacts if the systematic effects of soil moisture modifications are larger than the inherent simulation uncertainty at the convection resolving scale.

We performed seven experiments with either modified soil moisture amount or distribution to address the effect of soil moisture on precipitation. Each of the experiments consists of ten ensemble members using the deep convection resolving COSMO model with a grid spacing of 2.8 km. In three out of the seven experiments, precipitation changes exceed the model spread in either amplitude, location or structure. These changes are caused by a 50% soil moisture increase in either the whole or part of the model domain or drying of the whole model domain. Increased or reduced soil moisture predominantly results in reduced precipitation rates. Replacing the soil moisture by a realistic field from different days has an insignificant influence on precipitation. We point out the need for uncertainty estimates in soil moisture studies based on convection resolving models.

1 Introduction

Convective precipitation changes rapidly in time and is very variable in space (Pedersen et al., 2010). The heterogeneity of convective precipitation and the interaction of different scales challenge atmospheric models on the global and regional scale. Nowadays, regional climate models operate with a horizontal resolution of 1 km and can represent convective processes explicitly to improve weather forecast (Mass et al., 2002). Nevertheless, precipitation formation results from a complex chain of atmospheric processes, which range from the microscale to the synoptic scale (Richard et al., 2007). Because many of these processes remain unresolved, precipitation features a highly uncertain quantity.

Soil moisture determines the partitioning of energy and the land surface and controls how much energy is used to heat up the surface or to moisten the atmosphere. The surface temperature plays a crucial role in the initiation of convection, whereas the specific water content in the boundary layer modifies moist conditional instability. On the one hand, high surface temperatures initiate convection with a low soil moisture content. On the other hand, high soil moisture can destabilize the atmosphere by introducing water vapor in the lower troposphere resulting in an enhanced possibility for convection. Accordingly, there is no distinct effect from soil moistening or drying on precipitation intensification. In contrast, there exists a strong systematic influence of soil moisture changes on latent and sensible heat fluxes as well as on equivalent potential temperature, lifting condensation level, and convective energy (Barthlott et al., 2011). Despite these systematic effects, precipitation reacts less systematically to soil moisture variations (Barthlott and Kalthoff, 2011; Hohenegger et al., 2009). The distribution and inhomogeneity of soil moisture patterns may even initiate secondary circulation (Clark et al., 2004; Adler et al., 2011; Kang and Bryan, 2011; Dixon et al., 2013; Maronga and Raasch, 2013; Froidevaux et al., 2014).

There is no clear agreement on soil moisture - precipitation interaction in the literature: Barthlott et al. (2011) found a strong influence on precipitation, with changes larger than 500% for a soil moisture variation of $\pm 25\%$ in regions with low mountain ranges, and changes of up to -75% for domains with higher mountain ranges. They could not identify significant differences between planetary boundary layer driven and synoptically forced conditions. Hauck et al. (2011) determined large systematic differences between simulated and observed soil moisture. The influence on simulated precipitation in their study was complex and strongly dependent on the chosen case and domain. A dependency of all convective indices on the equivalent potential temperature was found by Kalthoff et al. (2011) over different orographic terrains. However, convection was predominantly initiated over mountain crests, independently of the instability indices, but with smaller convective inhibition (CIN). The dependency of equivalent potential temperature on soil moisture was found to be influenced by surface inhomogeneity. Barthlott and Kalthoff (2011) provide a sensitivity study in which the soil moisture was changed by $\pm$ 50% in steps of 5%. While the study reveals a systematic effect on the 24 hours precipitation sum for reduced soil moisture, precipitation is not systematically modified by wetter soil moisture conditions.

Large variations in the results may partly be attributed to model uncertainty. Hohenegger and Schär (2007) investigated the error growth of random perturbation methods in cloud-resolving models using time shifted model simulations and perturbed temperature fields in the initial conditions. ~~In their model study~~, using a model resolution of 2.2 km, a rapid error growth was found far away from the perturbed regions, but growth of uncertainties is limited by the large-scale atmospheric environment. A further aspect causing model uncertainty is model resolution, especially regarding the influence on convection. Different results for soil moisture-precipitation feedback also appear in simulations with explicitly resolved and differently parametrized convection (Hohenegger et al., 2009). Hohenegger et al. (2008) found different results in sign and strength of the influence of soil moisture that depend on the model resolution. Simulations with explicitly resolved convection indicate a negative soil moisture-precipitation feedback that is in agreement with many other studies, summerised by Barthlott and Kalthoff (2011).

In numerical weather prediction models, soil moisture perturbations are used to generate the ensemble members. Weather services include soil moisture perturbation in data assimilation for their ensemble forecast systems. For example, MeteoSwiss