Advances in Water Resources 83 (2015) 240–249

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

The subsurface–land surface–atmosphere connection under convective conditions

M. Rahman [a,1,*], M. Sulis [a], S.J. Kollet [b,c]

[a] Meteorological Institute, University of Bonn, Germany
[b] Agrosphere Institute, Research Centre Juelich, Germany
[c] Centre for High-Performance Scientific Computing in Terrestrial System, Geoverbund, ABC/J, Germany

ARTICLE INFO

Article history:
Received 18 February 2015
Revised 12 May 2015
Accepted 10 June 2015
Available online 14 June 2015

Keywords:
Coupled modeling
Groundwater dynamics
Soil moisture
Convective precipitation

ABSTRACT

The dynamics of the free groundwater table influence land surface soil moisture and energy balance components, and are therefore also linked to atmospheric processes. In this study, the sensitivity of the atmosphere to groundwater table dynamics induced heterogeneity in land surface processes is examined under convective conditions. A fully coupled subsurface–land surface–atmosphere model is applied over a 150 km × 150 km study area located in Western Germany and ensemble simulations are performed over two convective precipitation events considering two separate model configurations based on groundwater table dynamics. Ensembles are generated by varying the model atmospheric initial conditions following the prescribed ensemble generation method by the German Weather Service in order to account for the intrinsic, internal atmospheric variability. The results demonstrate that especially under strong convective conditions, groundwater table dynamics affect atmospheric boundary layer height, convective available potential energy, and precipitation via the coupling with land surface soil moisture and energy fluxes. Thus, this study suggests that systematic uncertainties may be introduced to atmospheric simulations if groundwater table dynamics are neglected in the model.

1. Introduction

In the terrestrial hydrological cycle, subsurface, land surface, and atmospheric processes are related via complex feedback mechanisms, which have been subject of research for some time [e.g., 9,14,23,43,60]. Several previous studies have shown that the land–atmosphere interaction is significantly influenced by the heterogeneity of land surface processes [e.g., 1,53,83]. An important aspect of heterogeneity in land surface processes is the variability of shallow soil moisture [e.g., 52]. The impact of land surface soil moisture variability on the atmosphere has been shown previously using observations [e.g., 24,37,74] and model results [e.g., 34,38,61,65,72,81]. Variability in land surface soil moisture influences surface energy partitioning, which eventually affects atmospheric processes, such as convective precipitation [e.g., 16,17,33,73]. Hohenegger et al. [29] studied soil moisture-precipitation feedback mechanisms over Alpine regions and showed that the variability in shallow soil moisture creates significant differences in simulated convective precipitation. Hauck et al. [28] showed the influence of land surface soil moisture on convective processes over complex terrains and discussed the importance of realistic soil moisture initialization for weather prediction models. Juang et al. [32] studied the triggering mechanisms of summertime convective precipitation and suggested that a negative feedback between land surface soil moisture state and convection exists, i.e., convective precipitation may be triggered over dry regions. Froidevaux et al. [25] also demonstrated a negative soil moisture-convection feedback in idealized simulations and discussed the influence of background wind on this mechanism. These studies suggest that there exists a strong link between land surface hydrology and atmospheric processes especially under convective conditions.

In order to illustrate land–atmosphere connection, the aforementioned studies generated heterogeneity in land surface soil moisture via arbitrary or statistical perturbation. However, soil moisture heterogeneity resulting from physical processes (e.g., groundwater dynamics) may also affect atmospheric processes, which is not yet well-understood. In the coupled water and energy cycles of the terrestrial system, the groundwater table acts as the lower boundary condition (LBC) that influences land surface mass and energy balance components [e.g., 22,36,55,75]. Demonstrating the interactions between this LBC and the land surface mass and energy fluxes has been the focus of several previous studies [e.g., 40,46,69]. The effect of groundwater table depth (WTD) on surface runoff [e.g., 39,82] and evapotranspiration [49,70] is well-established. Chen and Hu [15]

* Corresponding author.
E-mail address: ar15645@bristol.ac.uk (M. Rahman).
1 Present address: Department of Civil Engineering, University of Bristol, UK.

http://dx.doi.org/10.1016/j.advwatres.2015.06.003
0309-1708/

showed that the influence of subsurface hydrodynamics on root zone soil moisture depends on WTD. Miguez-Macho and Fan [50] demonstrated the effect of groundwater dynamics on seasonal soil moisture over the Amazon region. The subsurface–land surface connection with respect to the scaling properties of groundwater dynamics has also been discussed previously in several studies [e.g., 2,42,62]. From these studies it is evident that WTD influences land surface mass and energy balance components including soil moisture.

Although the aforementioned studies show the interconnections between various compartmental processes of the hydrological cycle, the influence of LBC dynamics (i.e. water table dynamics) on atmospheric simulations via land surface mass and energy fluxes remains largely unresolved. As aforementioned, studies discussing the influence of land surface soil moisture on atmospheric processes generally perturb the soil moisture state arbitrarily in the simulations and demonstrate the influence on simulated mass and energy balance components [e.g., 28,29]. However, as discussed earlier, the LBC dynamics affect land surface soil moisture, which may eventually affect the atmospheric processes. Few studies have discussed the relationship between groundwater dynamics and atmosphere via land surface processes previously [e.g., 12,45]. Quinn et al. [54] coupled the hydrologic TOPMODEL with a single-column boundary layer model (SLAB) and discussed groundwater– atmospheric boundary layer connection via land surface energy fluxes. Maxwell et al. [47] showed the correlation between WTD and several atmospheric variables, e.g., atmospheric potential temperature and boundary layer height. Anyah et al. [3] demonstrated that especially over convection-dominated regimes, groundwater influences precipitation by modifying evapotranspiration. Jiang et al. [30] argued that groundwater plays an important role on precipitation persistence in regional climate models. Campoy et al. [13] studied the effect of hydrological bottom boundary condition of land surface models on shallow soil moisture and argued that this subsurface–land surface connection may affect atmospheric processes, e.g., precipitation. Barlage et al. [7] demonstrated the effect of deep groundwater on regional climate simulations. Despite the aforementioned studies suggest that the LBC dynamics influence atmospheric processes, the impact of groundwater dynamics on atmosphere in a fully coupled model that simulates subsurface, land surface, and atmospheric processes consistently is not yet well-discussed.

This study examines the sensitivity of simulated atmospheric processes to WTD induced modifications in land surface mass and energy balance components under convective conditions. We hypothesize that groundwater dynamics influence convective initiation through the coupling with atmosphere via soil moisture and land surface energy fluxes, and, thus, may introduce systematic uncertainties, if groundwater dynamics are neglected. We apply the coupled simulation platform TerrSysMP [67] to a regional scale catchment (on the order of 10^4 km^2) in Western Germany and simulate the mass and energy balance components of the hydrological cycle from groundwater across the land surface into the atmosphere.

In order to identify the influence of LBC on the mass and energy balance components, simulations are performed considering two different WTD configurations, namely, dynamic and constant lower boundary conditions (DBC and CBC, respectively). The dynamic lower boundary condition (DBC) configuration allows the temporal evolution of groundwater, while constant lower boundary condition (CBC) configuration maintains a temporally constant WTD throughout the simulation period. Ensemble simulations are performed by perturbing the initial conditions to deal with the internal variability in atmospheric simulations. As a first step, we show the change in atmospheric processes (e.g., precipitation, atmospheric boundary layer height, and convective available potential energy) between DBC and CBC model configurations. Finally, we interpret the interactions between the compartmental processes in our simulation results as a possible reason of the sensitivity of atmospheric processes to LBC.

2. Methods

2.1. Study area

The model domain (Fig. 1) is located in the Western Germany with an area of 2.25×10^4 km^2 encompassing the Rur catchment [10,68,78]. The southern part of the model domain is characterized by the mountainous Eifel region, which is forested with mainly coniferous trees. This mountainous region receives an annual precipitation of about 1000–1200 mm. In contrast, the northern part of the study area is characterized by flat lowland regions with an annual precipitation amount of about 550–600 mm/a. In this part of the area, agriculture is the major land use type with cereals (e.g., winter wheat)

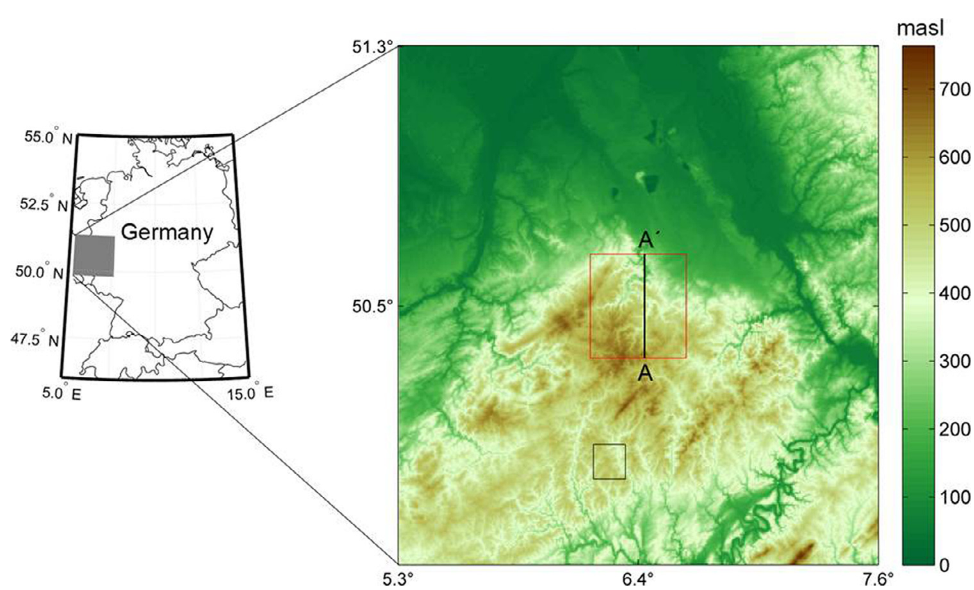

Fig. 1. Location (left) and topography (right) of the study area. The red box (30 km × 30 km) shows the area used for spatial averaging in Figs. 3a, 4a, and 5. The black box (10 km × 10 km) bounds the area used for spatial averaging in Figs. 3b and 4b. AA′ shows the cross-section used in Fig. 6. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)