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Improving the representation of river–groundwater interactions in land surface modeling at the regional scale: Observational evidence and parameterization applied in the Community Land Model

M. Zampieri [a,b,*], E. Serpetzoglou [c], E.N. Anagnostou [a,d], E.I. Nikolopoulos [a], A. Papadopoulos [a]

[a] Institute of Inland Waters, Hellenic Center for Marine Research, Anavissos, Greece
[b] Physical Sciences and Engineering Division, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia
[c] Department of Meteorology and Climatology, School of Geology, Aristotle University of Thessaloniki, Thessaloniki, Greece
[d] Civil and Environmental Engineering, University of Connecticut, Storrs, USA

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SUMMARY

Groundwater is an important component of the hydrological cycle, included in many land surface models to provide a lower boundary condition for soil moisture, which in turn plays a key role in the land–vegetation–atmosphere interactions and the ecosystem dynamics. In regional-scale climate applications land surface models (LSMs) are commonly coupled to atmospheric models to close the surface energy, mass and carbon balance. LSMs in these applications are used to resolve the momentum, heat, water and carbon vertical fluxes, accounting for the effect of vegetation, soil type and other surface parameters, while lack of adequate resolution prevents using them to resolve horizontal sub-grid processes. Specifically, LSMs resolve the large-scale runoff production associated with infiltration excess and sub-grid groundwater convergence, but they neglect the effect from loosing streams to groundwater. Through the analysis of observed data of soil moisture obtained from the Oklahoma Mesoscale Network stations and land surface temperature derived from MODIS we provide evidence that the regional scale soil moisture and surface temperature patterns are affected by the rivers. This is demonstrated on the basis of simulations from a land surface model (i.e., Community Land Model – CLM, version 3.5). We show that the model cannot reproduce the features of the observed soil moisture and temperature spatial patterns that are related to the underlying mechanism of reinfiltration of river water to groundwater. Therefore, we implement a simple parameterization of this process in CLM showing the ability to reproduce the soil moisture and surface temperature spatial variabilities that relate to the river distribution at regional scale. The CLM with this new parameterization is used to evaluate impacts of the improved representation of river–groundwater interactions on the simulated water cycle parameters and the surface energy budget at the regional scale.

1. Introduction

Groundwater is a basic component of the hydrosphere and plays a fundamental role in many processes that affect the atmosphere and the biosphere. Groundwater sustains streams, lakes, wetlands and the related ecosystems (Alley et al., 2002; Dahm et al., 2003). It provides a lower boundary condition for soil moisture and a direct source of water for plant roots, thus affecting evapotranspiration, especially in warm periods and shallow water table conditions (Schmidhalter et al., 1994; Snyder and Williams, 2000; Scott et al., 2006; Steinwand et al., 2006; Yeh and Famiglietti, 2009; Xie and Yuan, 2010), and the carbon cycle (Ju et al., 2006). Soil moisture, in turn, affects surface temperature through the control on the partitioning of sensible and latent heat flux (Zampieri et al., 2009 and references therein).

Groundwater is implicitly accounted in the land surface schemes of many climate models for the computation of surface and sub-surface runoff (Koster et al., 2000; Ducharne et al., 2000; Walko et al., 2000; Chen and Kumar, 2001; Seuffert et al., 2002; Gedney and Cox, 2003; Yang and Niu, 2003; Niu and Yang, 2003; Niu et al., 2005). A number of these models follow the TOPMODEL approach (Beven and Kirkby, 1979) assuming that, for each grid cell of the model, ponded areas exist because of the interaction of groundwater dynamics and subgrid orography. Therefore, runoff production is expected to increase in case of shallow water table. The TOPMODEL can be considered as a one-way surface–groundwater interaction model, which accounts for the flux of

* Corresponding author at: Physical Sciences and Engineering Division, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia. Tel.: +966 28080272.

E-mail addresses: Matteo.Zampieri@kaust.edu.sa, M.Zampieri@isac.cnr.it (M. Zampieri).

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water from the saturated zone to the surface. Many studies have explicitly accounted for the groundwater to improve the soil moisture and evapotranspiration representation in the land surface schemes for the general circulation models and regional climate models (Famiglietti and Wood, 1994; Stieglitz et al., 1997; Gutowski et al., 2002; York et al., 2002; Liang et al., 2003; Maxwell and Miller, 2005; Yeh and Eltahir, 2005a,b; Cohen et al., 2006; Niu et al., 2007; Miguez-Macho et al., 2007; Anyah et al., 2008; Yuan et al., 2008; Jiang et al., 2009, see also Fan et al., 2007 for a review). These studies have shown that incorporating the water table dynamics enhances modeled evapotranspiration and eventually reduces bias in the simulated precipitation, especially in the warm season of humid and semi-humid climates, as for instance monsoon-influenced climates. In fact, in regions with shallow water table, groundwater can determine the soil moisture profile and provide a direct source of water for transpiration, thus increasing the "memory" of soil conditions to precipitation and enhancing the persistence of intraseasonal and interannual precipitation in regional climate models, as suggested by Bierkens and van der Hurk (2007).

An important source of groundwater is reinfiltrated water from streams (Sophocleous, 2002). This process can be simulated explicitly at the river scale (Osman, 2002), and at the watershed scale through high-resolution coupled land surface–groundwater models (Kollet and Maxwell, 2006). It is usually neglected in regional land surface models (LSMs) because of the lack of resolution that is needed to simulate the local infiltration of river water and the lateral hydrological processes along river corridors. As noted by Zhang and Montgomery (1994), a good representation of these lateral processes requires a spatial scale of at least 10 m resolution while a representative LSM scale in regional climate applications is 20–50 km. River transport models (RTMs) are used in some LSMs to simulate fresh water fluxes into the oceans that is needed to close the global water budget. However, the interaction of river water with groundwater is generally neglected in these models.

Studies have shown that rivers and stream–groundwater interactions are responsible for the lagged correlation between precipitation over the mountains and wetter soils over the planes (Kingston et al., 2009; Wedgbrow et al., 2002). Consequently, lack of proper representation of these processes in the climate models could result in biases in the simulated surface climate. Furthermore, stream–groundwater dynamics can alter the spatial variability in the soil moisture field that could influence the local atmospheric circulation and moist convection (Weaver, 2006; Steiner et al., 2009) with feedback effects on the surface climate itself. Unfortunately, a direct validation of LSMs in terms of comparison with observed groundwater or soil moisture data is difficult, because data are sparse and representative of very small areas relative to a typical LSM grid resolution. However, changes in the hydrological cycle could be investigated through the indirect effect on surface temperature, for which satellite products exist at the desired resolution and spatial coverage. This is an aspect we explore further in this research.

River–groundwater interaction at the local scale can be parameterized in terms of the difference between the river elevation and a reference groundwater head through the concept of river conductance (Rushton, 2007). At the regional scale the limited resolution does not provide the sufficient information needed to apply the river conductance method. Miguez-Macho et al. (2007) generalized this approach and proposed a regional groundwater model with a parameterization of river–groundwater interactions. To circumvent the resolution problem, river conductance was parameterized as a function of the displacement of the water table depth with respect to its equilibrium value and the mean river elevation, which are computed a priori from a preliminary 1-km resolution groundwater simulation (Fan et al., 2007). However, the river–groundwater interaction itself was not validated as the study focused on addressing the sensitivity of the groundwater model with respect to the free-drainage condition. The importance of improving the river hydrology in the models is also pointed out by David et al. (2009), who integrated a vector representation of the stream and river network derived by 30 m topography in the high-resolution NOAH-distributed land surface model (Gochis and Chen, 2003).

In this paper, we provide observational evidences that soil moisture and surface temperature spatial distributions are related to the characteristics of the river network at regional scale (0.25°). At this resolution, we hypothesize that the mean effect can be modeled as a direct water flux from the river reservoir to the mean groundwater for each grid point in the same spirit of the TOPMODEL approach, but to describe the opposite process. In this framework, the sub-grid mechanisms that are responsible for the mean effect, i.e., the local infiltration at the scale of the river, the lateral hydrological processes along the river corridors, and the lateral groundwater fluxes that redistribute the local water anomaly at the grid scale, are accounted implicitly. We demonstrate the validity of this assumption by comparing observations and simulations conducted with the Community Land Model (CLM), version 3.5 (Oleson et al., 2004, 2008), that we modified to include the new parameterization.

This paper is organized as follows: the following section (Section 2) includes a description of the study region and the data used. In Section 3, we describe the CLM model, in particular the groundwater dynamics in the original version as well as our modification that accounts for the river feedback, and the control simulation used to analyze the observed data. In Section 4, we discuss the observational analysis of the soil moisture and temperature data showing their dependency of the regional scale characterization of rivers. In Section 5, we present the results of the new parameterization introduced in CLM, and we quantify the impact of this parameterization on the water cycle and the land surface state. Discussion, conclusions and prospects for future work are provided in Section 6.

2. Study region and data

Fig. 1 shows the stations locations and the mesh over which the observed data are interpolated. The study region is in the State of Oklahoma (US), where a dense network of hydrometeorological stations is present (Mesonet; Brock et al., 1995; Shafer et al., 2000). This network provides basic surface (e.g., precipitation, solar radiation and pressure) and near-surface (e.g., 10-m height temperature, relative humidity and wind) meteorological observations as well as soil moisture measurements at four different depths (5, 25, 60 and 75 cm), which comprise the focus of our analysis. A gridded version of the Mesonet database is used for the period 2000–2006, created by means of interpolating the original point meteorological observations on a 0.25° grid from 34.5N to 37N and 100W to 94.5W (10×22 grid). The Mesonet meteorological data were interpolated to this spatial grid using the inverse distance weighting (IDW) technique. The first 4 years of data (2000–2003) are used to initialize the land surface model and the last 3 years (2004–2006) are used for the actual soil moisture analysis and the sensitivity studies.

Fig. 2 shows the average precipitation and root zone soil moisture from January 2004 to December 2006 computed on the grid mesh presented above. The root zone soil moisture is defined as the arithmetic average of the observations at 5, 25, 60 and 75 cm depths (Teuling et al., 2006; Albergel et al., 2008). Both precipitation and soil moisture show a zonal gradient, with a drier climate in the west side of the domain and a more humid climate in the east side. Their patterns show regional features that are correlated to each other, e.g., precipitation and soil moisture exhibit local minima on the west side of the domain and local maxima in the