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Benefit of coupling the ISBA land surface model with a TOPMODEL hydrological model version dedicated to Mediterranean flash-floods

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SUMMARY

The ISBA land surface model and a version of the TOPMODEL hydrological model have been coupled to simulate Mediterranean flash-floods. This coupling makes use of the watershed topography to compute the sub-surface lateral water fluxes and spatial and temporal dynamics of the saturated areas, following the TOPMODEL principles. The ISBA model governs the overall water budget and estimates the runoff supplied to the flow routing model.

When applied to six flash-flooding events that occurred recently over South-eastern France the coupled system proved its ability to better forecast both timing and intensity of the flood peaks compared with the ISBA model used alone. To highlight further the differences between the two systems, an idealized framework was set up. The benefit of using ISBA–TOPMODEL instead of the ISBA model alone is clearly shown and leads to more physically consistent soil moisture and discharge simulations. The coupled system is able to simulate soil moisture and discharges that are not only governed by the rainfall, but also by the topography of the watershed.

1. Introduction

The Northwestern Mediterranean is prone to heavy rainfall events that lead to flash-floods over the small to medium basins of this region (ranging from 10 km^2 to 2000 km^2) especially during the fall season. Either quasi-stationary mesoscale convective systems, which can last several hours, or frontal disturbances blocked by the mountains can produce high precipitation totals (Nuissier et al., 2008) that trigger severe flash-floods (Delrieu et al., 2005). The hydrological response of those watersheds has been found to be mainly driven by runoff over saturated areas (Cosandey and Didon-Lescot, 1990; Lardet and Obled, 1994; Taha et al., 1997; Saulnier and Datin, 2004). Some hydrological models were then developed to represent such kind of hydrological behaviour and were evaluated on these regions (Pellarin et al., 2002; Le Lay and Saulnier, 2007). Most of them are based on the TOPMODEL framework (Beven and Kirkby, 1979; Beven et al., 1995) which makes use of spatial variabilities such as the topography. TOPMODEL introduced the concept of hydrological similarity and it was one of the first attempts to model distributed hydrological response based on the process of runoff on saturated areas (Dunne and Black, 1970).

Although this process is now quite well established as the dominating one in these regions, it is not the only ingredient to take into account when modelling severe flash-floods. Previous sensitivity studies showed that the spatial and temporal rainfall forcing and the spatial distribution of the initial soil water state of the watersheds are also two key factors explaining the performance of such hydrological models (Le Lay and Saulnier, 2007; Saulnier and Le Lay, 2009). Particular attention must thus be paid to rainfall and evapotranspiration estimation. In other words, coupling hydrological models with Soil Vegetation Atmosphere Transfer (SVAT) schemes could be beneficial to simulate distributed flash-floods generation over Mediterranean watersheds.

Since the beginning of the 1990s, such studies on the coupling between evaporation and transpiration modelling (SVAT schemes)

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and soil infiltration, runoff genesis and flood propagation modelling (hydrological models) were carried out (Wood et al., 1992; Famiglietti and Wood, 1994a,b; Stieglitz et al., 1997; Wooldridge et al., 2003) and are still an on-going research topic. These studies about coupling usually aimed at improving the runoff computation within SVATs using a hydrological model as a subgrid runoff parameterization (Warrach et al., 2002; Stieglitz et al., 1997; Koster et al., 2000; Ducharne et al., 2000). Such couplings were in particular developed for ISBA (Noilhan and Planton, 1989) and TOPMODEL, i.e. the models used in this study. Habets and Saulnier (2001) used the TOPMODEL topographic index within the two-layer (the surface and root layers) version of ISBA in order to replace the conceptual VIC subgrid runoff parameterization (Dümenil and Todini, 1992). Pellenq et al. (2003) used also the TOPMODEL formalism to spatially disaggregate the ISBA generated soil moisture based on topography and soil depth. More recently, Decharme and Douville (2006) extended this work to the ISBA-3L version where a third soil layer is more specifically dedicated to hydrology (Boone et al., 1999). This study also showed an improvement of the simulated catchment water budget. However these studies were limited to a 1D-vertical coupling with no lateral flow of soil water between neighbouring grid meshes. This study was also carried out at seasonal and regional scales, using a global statistical description for topography rather than the fine scale topography of the watersheds. Only few studies have implemented a full coupling between a SVAT scheme and an hydrological model, i.e. not only a hydrological subgrid parameterization but also including other hydrological processes such as the discharge propagation within the river network (Walko et al., 2000; Seuffert et al., 2002). However the benefit of such coupling for quantitative discharge forecast has not already been studied.

Our study goes one step further in the modelling of the coupled hydro-meteorological processes by designing and evaluating a full 2-way coupling between the ISBA-3L SVAT model and the TOPMODEL hydrological model to simulate flash-flooding at the event scale. The runoff generation is still computed as a subgrid parameterization of the SVAT model, i.e. within a 1D vertical column but the hydrological model estimates the lateral sub-surface water fluxes within the soil layers and between neighbouring SVAT grid meshes. The hydrological model also computes the propagation of the hillslope runoff and the discharges within the river network. This coupling may then be seen as a split between the 1D processes (evapotranspiration, porous media infiltration) which are modelled by the SVAT at its own scale and the 2D processes (sub-surface lateral water fluxes, runoff and flood propagation) which are represented by the distributed hydrological model at its own and finer resolution. The runoff on saturated areas is computed following the method used in TOPODYN, a Mediterranean flash-flood dedicated version of TOPMODEL (Pellarin et al., 2002). Indeed, this runoff estimation is particularly dedicated to the hydro-meteorological context of the Northwestern Mediterranean region as it allows to take into account the high spatial variability of the Mediterranean precipitation events through a temporally dynamic hydrological index. The distribution of water within the catchment is not only based on topographic information but also on the variability of the rain over the watershed. The benefit of having coupled a SVAT model with a hydrological model dedicated to the simulation of flash-floods is illustrated in the present study both on real cases and for idealized conditions.

The outline of the paper is as follows. Section 2 describes the principles of this new coupling between ISBA-3L and TOPMODEL. Results of its application to six recent flash-flood events are discussed in Section 3. Then, a detailed analysis of the benefits of the coupled system is carried out in Section 4 thanks to idealized simulations. Concluding remarks follow in Section 5.

2. The ISBA–TOPMODEL coupled system

Like most of land surface models, ISBA aims to best represent the water and energy fluxes between the land surface and the atmosphere. A high emphasis in ISBA was thus given to the representation of one-dimensional vertical processes (evapotranspiration, infiltration, gravitational drainage, vertical soil moisture diffusion, etc.) based on the force-restore method (Deardorff, 1977, 1978). The 3-layers ISBA version is used here with a 1-km regular grid covering the Cévennes–Vivarais region (Fig. 1). A first very thin surface layer interacts with the atmosphere and has a uniform depth (d_1). Then a root zone of depth d_2 is dedicated to the management of available water for plants. At last, a deep-soil zone ends at depth d_3 below which soil moisture does not vary anymore. The sub-surface runoff is produced when the soil layers

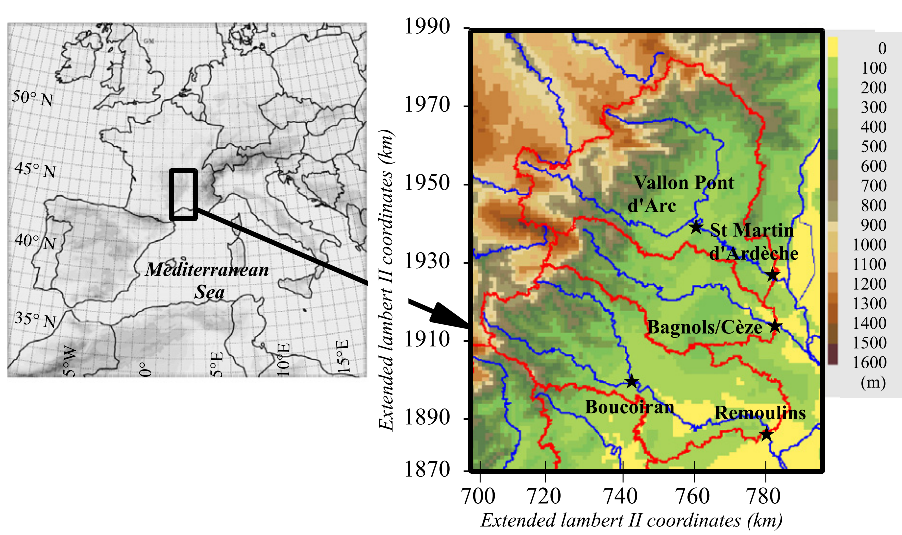

Fig. 1. The ISBA domain enclosing the Cévennes–Vivarais watersheds together with model terrain (in meter) at 1 km^2 resolution. Rivers are shown as blue lines whereas the red lines delineate the main watersheds. Stars indicate the main outlets: St. Martin for the Ardèche river (2240 km^2), Bagnols for the Cèze river (1110 km^2), Boucoiran for the Gardons river (1090 km^2) and Remoulins for the Gard river (1910 km^2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)