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Research papers

A framework to improve hyper-resolution hydrological simulation in snow-affected regions

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A B S T R A C T

Snow processes in mid- and north-latitude basins and their interaction with runoff generation at hyper-resolution (<1 km and <hourly) pose challenges in current state-of-the-art distributed hydrological models. These models run typically at macro to moderate scales (>5 km), representing land surface processes based on simplified couplings of snow thermal physics and the water cycle in the soil-vegetation-atmosphere (SVA) layers. This paper evaluates a new hydrological model capable of simulating river flows for a range of basin scales (100 km^2 to >10,000 km^2), and a particular focus on mid- and north-latitude regions. The new model combines the runoff generation and fully distributed routing framework of the Coupled Routing and Excess STorage (CREST) model with a new land surface process model that strictly couples water and energy balances at the SVA layer, imposing closed energy balance solutions. The model is vectorized and parallelized to achieve long-term (>30 years) high-resolution (30 m to 500 m and subhourly) simulations of large river basins utilizing high-performance computing. The model is tested in the Connecticut River basin (20,000 km^2), where flooding is frequently associated with interactions of snowmelt triggered by rainfall events. Model simulations of distributed evapotranspiration (ET) and snow water equivalence (SWE) at daily time step are shown to match accurately ET estimates from MODIS (average NSCE and bias are 0.77 and 6.79%) and SWE estimates from SNODAS (average correlation and normalized root mean square error are 0.94 and of 19%); the modeled daily river flow simulations exhibit an NSCE of 0.58 against USGS streamflow observations.

1. Introduction

The water cycle has been extensively studied in terms of land surface modeling (Liang et al., 1994; Ludwig and Mauser, 2000; Wang et al., 2011), yet in mid- and high-latitude regions affected by heavy snow, acceptable performance with a hydrological model is difficult to achieve (Parr et al., 2015). The snow accumulation and melting process in these regions greatly affects both thermal and water budgets (Anderson, 2006, 1976; Bartelt and Lehning, 2002; Lehning et al., 2002a), which in turn control evapotranspiration, soil temperature, and soil moisture calculations. These processes that greatly impact spring flow simulations have been studied extensively by both hydrological and snow process modeling groups. In forested areas, great efforts have been exerted to simulate snow processes (Anderson, 1976; Andreadis et al., 2009; Bartelt and Lehning, 2002; Lehning et al., 2002a; Lehning et al., 2002b). Even after calibration, however, these model simulations and observations have agreed only on annual amounts, while the uncertainty in daily values is considerable. This land surface modeling uncertainty has a great impact on flow simulations (Essery et al., 2009). In addition, most aforementioned snow models are designed merely for one-dimensional simulations, while the distributed hydrological models are suitable for simulations at moderate (>5 km) to macro (>1/8°) scales.

Current hydrological models use concepts from snow models by fully or loosely coupling with their original land surface schemes. For this paper, we applied a strictly closed energy balance (EB) solution to represent snow-affected water cycle processes and interactions with vegetation in forested areas. The difficulty of solving EB lies in structuring the air-vegetation-soil layers under various land surface conditions, formulating thermal/water balance equations within layers and flux/mass exchanges between layers, deriving distributed parameters, and making the nonlinear system within every grid cell converge efficiently. The computations become more challenging when these processes are to be resolved over large regions (ranging from large basins to continents) and long periods (multiple decades) at fine spatiotemporal scales.

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Originating from lumped hydrological models, the linear reservoir routing (LRR) can also been extended to distributed hydrological models with promising efficiency and acceptable accuracy, such as the parallel linear reservoir (PLR) (Archer et al., 2000) and fully distributed linear reservoir (FDLRR) (Shen et al., 2016).

Here we describe the development and evaluation of a new model aimed at improving the accuracy of hydrological simulations in snow- and forest-covered regions at fine spatiotemporal resolution (30 m to 500 m and hourly time steps) and for long periods (35 years to 50 years). Specifically, we extended the distributed hydrological framework of the Coupled Routing and Excess STorage (CREST) model (Wang et al., Shen et al., 2016) to physically integrate hydrological and snow processes, including vegetation interception, evapotranspiration, soil infiltration and snow accumulation, melting, and refreezing. Furthermore, parameters of CREST's runoff generation module are distributed and can be physically derived, while the routing parameters are uniform and can be optimized based on observed stream flow data.

In the next section we describe the development of the model, including its land surface structure and the methodology implemented for coupling water and energy balances. In Section 3 we describe the model validation over the Connecticut River. We discuss the model performance evaluation in Section 4, and in Section 5 we present our conclusions and thoughts on future directions. Abbreviations used in this paper are defined in Table 1.

2. Methodology

2.1. Model overview

We selected the CREST hydrological model as the framework for this study because of its computationally efficient, fully distributed routing module (Shen et al., 2016) that can run large basin ($\sim 10^6$ km^2) simulations at fine spatiotemporal resolution (30 m to 1 km spatial grid resolution and hourly time steps) over long periods (a few decades). However, CREST's current simple runoff generation scheme does not explicitly account for vegetation structure or the energy balance—processes that are critical for mid- and high-latitude regions affected by mixed phase precipitation.

In this paper, we extended the CREST model implementing a physically-based runoff generation module that explicitly represents the different vegetation structures and snow processes, as depicted in Fig. 1.The runoff generation module solves for the coupled water and energy balances, using as input dynamic variables—namely, meteorological variables (precipitation, radiation, humidity, wind speed), and leaf area index (LAI)—and static parameters—land cover, soil properties, vegetation species descriptions, and impervious ratios. The new version of CREST is named CREST-SVAS to represent the model's extension in terms of soil-vegetation-atmosphere-snow (SVAS) processes.

Table 1
Abbreviations used in this paper.

Abbreviation	Full Name
CREST	coupled routing and excess storage
SVA	soil-vegetation-atmosphere
SVAS	soil-vegetation-atmosphere-snow
ET	evapotranspiration
SWE	snow water equivalence
EB	energy balance
LAI	leaf area index
NSCE	Nash-Sutcliffe efficiency coefficient
RMSD	root mean squared difference
NRMSD	normalized root mean squared difference
HPC	high performance computer
VIC	variable infiltration capacity

2.2. Characterization of the Soil-vegetation-atmosphere structure

To compute the redistribution of precipitation at the vertical dimension, water and thermal balances must be simultaneously solved. In a given layer, we solve water balance for the water availability, which in turn greatly affects the temperature we solve for in the thermal balance. Knowing the temperature change, we can then estimate the amount of energy that is spent in changing the phase and amount of water.

Accurate modeling of the water and temperature variables depends primarily on the characterization of soil-vegetation-atmosphere (SVA) interactions through coupling of the water and thermal balances. Conceptually, we classify plants into two categories: with canopy and without canopy. The former are able to intercept both snowfall and rainfall, while the latter can only intercept rainfall. Considering the thermal insulator property of snow, temperature differences may occur between the canopy layer, adjacent air and encapsulating air of the canopy layer. The SVA, therefore, is thermally divided into, at most, five layers, as shown in Fig. 1. The snowpack layer vanishes when the ground has no snow accumulation, as does the atmospheric layer when there is no intercepted snow. Snowpack is divided into two layers, the surface layer and pack layer, to mimic the thermal insulator function of a snow layer between soil and air. As in (Liang et al., 1999), soil is thermally divided into two layers and physically divided into three layers. The coupled water and energy balance computational steps based on this conceptual structure are depicted in Fig. 2.

2.3. Water balance

Water exchanges in the rainfall runoff generation module include the interception of precipitation and evapotranspiration (ET) by vegetation; the accumulation and melting of the snow pack, its refreezing, and, finally, the outflow of the pack water; and the percolation by water of multiple soil layers. When precipitation first reaches the SVA structure, it undergoes the interception process if vegetation is present. Then, through-fall triggers the snow accumulation or melting process on the ground if there is snow or if the though-fall itself contains snow. Finally, the outflow from the snowpack or, in a snow-free grid, the through-fall infiltrates soil layers. Meanwhile, ET is taking place, including the evaporation and/or sublimation and/or from intercepted water and transpiration by plants.

2.3.1. Interception by vegetation

Precipitation is partitioned into snowfall and rainfall as a function of surrounding air temperature (Anderson, 2006). Snow interception, then, consists of canopy area accumulation, the blowing of snow from the canopy by wind, and melting-triggered release. Based on previous findings on the dependence of snow interception on vegetation properties and climatic variables (Satterlund and Haupt, 1970), the maximal holding capacity of the canopy is proportional to the LAI (Kobayashi, 1987) and the canopy temperature (Ohta et al., 1993), and the increment of the interception during a time step is proportional to the snowfall (Storck et al., 2002). The snow blowing process is driven by wind speed, following Bowling et al. (2004). Similarly, liquid water interception capacity is affected by the intercepted snow, the LAI, and the temperature, following the method used by (Andreadis et al., 2009).

2.3.2. Snowpack accumulation and ablation

The precipitation remaining after the interception process, together with the released drips from the vegetation layer, form the through-fall precipitation. Solid water contained in the through-fall contributes to the formation of the snowpack on the ground surface, which may contain solid and/or liquid water (if