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Investigating the ability of a land surface model to simulate hydrological processes in cold and mountainous regions

OLGA N. NASONOVA, YEUGENIY M. GUSEV & EVGENY E. KOVALEV
Institute of Water Problems, Russian Academy of Sciences, Gubkina St. 3, 119333 Moscow, Russia
nasonova@aqua.laser.ru

Abstract The aim of the present work is to investigate the ability of a physically-based land surface model (LSM) SWAP, which treats energy and water exchange at the land–atmosphere interface, to simulate snow and runoff formation processes in mountainous and high latitude regions. Two regions characterised by different climatic conditions were selected for this study: the French Alps and pan-Arctic river basins located in Russia. In the first case, the results of snow depth simulations by SWAP were compared with daily snow depth measured during three years at 24 mountainous sites (with the altitudes varying from 910 to 2590 m). In the second case, snow depth and river runoff simulated by SWAP for several northern river basins on a long-term basis were validated against daily observations conducted during 20–30 years. It was concluded that, in general, SWAP can capture evolution of snowpack depth and runoff hydrographs and performs fairly well statistically.

Key words land surface model SWAP; snowpack; river runoff; cold regions; parameter optimization

INTRODUCTION

In this paper, among hydrological processes, the main emphasis will be on snow hydrology. Land surface models (LSMs) include different snow schemes ranging from the simplest implicit and composite layer schemes to a single bulk-layer and multi-layer ones. Evidently, snow representation in LSMs cannot be too sophisticated because it is limited by the requirement of numerical efficiency and because of the absence of regular measurements to derive snow parameters. The ability of LSMs to simulate snow processes was investigated within the framework of several international projects, in particular, PILPS-2d (Slater *et al*., 2001), PILPS-2e (Bowling *et al*., 2003), SnowMIP (Etchevers *et al*., 2004), Rhone-AGG (Boone *et al*., 2004) and SnowMIP2 (Rutter *et al*., 2009). All the projects have shown a great scatter in simulations of SWE or snow depth among the models. The same can be said about streamflow modelling. The aim of this paper is to investigate the ability of one of the land surface models used in the above projects, namely, the model SWAP (Soil-Water–Atmosphere–Plants), to simulate snow formation and runoff generation processes in cold and mountainous regions.

MODEL SWAP

The SWAP model, which has been developed by the authors since 1994, represents a physically-based land surface model that treats heat and water exchange at the land–atmosphere interface. The model structure, parameterizations used and the results of model validation were detailed in a number of publications (e.g. Gusev & Nasonova, 1998, 2002, 2003, 2004, 2010).

SWAP treats seasonal snowpack formation processes occurring at forested and open (non-forested) domains. In the case of forested surface, radiation, heat and water exchanges between the forest crowns and the forest floor are taken into account. Vegetation intercepts liquid and solid precipitation and snow formation processes occur both on the forest crowns and on the ground. They include accumulation of snow both in solid and liquid fractions, snow evaporation/sublimation and snowmelt. The latter occurs from the snow surface. Melt water can store in the snowpack, refreeze and generate water yield of snow cover. Liquid water holding capacity and thermal conductivity of snow are estimated in dependence on snowpack density. Densification of snow is taken into account through empirical dependence of snow density on snow water equivalent (SWE) and snow temperature. Albedo of ground snow pack depends on snow depth.

The model can be applied both for point (or grid cell) simulations of vertical fluxes and state variables of soil–vegetation/snow cover–atmosphere system and for simulating streamflow at different scales – from small catchments to continental-scale river basins under different natural conditions. In the case of a small river basin (up to the order of 10^3–10^4 km^2), a kinematic wave equation is used to simulate runoff at the basin outlet. In the case of a larger river basin, the basin area is divided into a number of computational grid cells connected by a river network. Runoff is modelled for each grid cell and then transformed by a river routing model to simulate streamflow at the river basin outlet (accounting for a contributing area of each cell). Herein, a simple linear transfer model in river channels to simulate river discharge of pan-Arctic rivers is used (Oki *et al.*, 1999).

DATA AND MATERIALS

Two regions characterised by different climatic conditions were selected for this study: the French Alps and two pan-Arctic river basins located in Russia.

French Alps sites The materials from the Rhone-AGG project (Boone *et al.*, 2004) for 24 mountainous sites located within the French Alps (Fig. 1) were used. The altitudes of the sites vary from 910 to 2590 m.

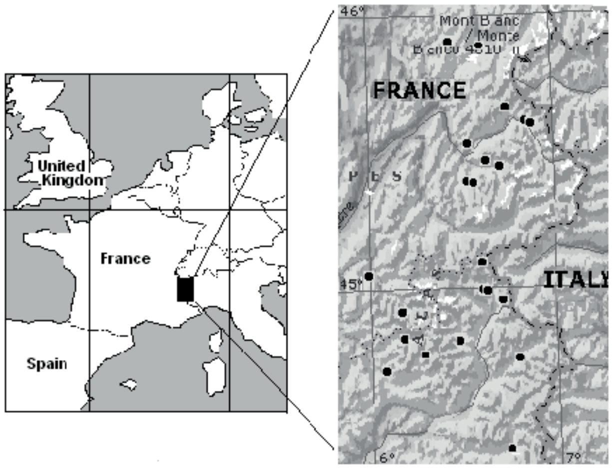

Fig. 1 Location of snow depth observation sites (black circles) in the French Alps.

The atmospheric forcing data and land surface parameters were taken from gridded data sets that were provided within the framework of the Rhone-AGG project at 8 km × 8 km spatial resolution. The atmospheric forcings were calculated using the SAFRAN (Systeme d'Analyse Fournissant des Renseignements Atmospheriques à la Neige: Analysis System for Providing Atmospheric Information Relevant to Snow) analysis system on the basis of standard meteorological observations at Meteo-France weather network sites, daily precipitation from a much more dense precipitation-gauge network, ECMWF (European Centre for medium-Range Weather Forecasts) analysis and climatological data for homogeneous climatic zones (Boone *et al.*, 2004). The atmospheric forcing data (including air temperature and humidity at 2 m, wind speed at 10 m, incoming shortwave and longwave radiation, precipitation, surface air pressure) were provided at 3-h time steps for a four-year period (from 1 August 1985 to 31 July 1989).

The provided soil parameters were defined using the soil textural properties (sand and clay fractions). The provided vegetation parameters were derived using a vegetation map from the Corine Land cover Archive and a two year satellite archive of AVHRR/NDVI (Boone *et al.*, 2004). We were free to specify snow parameters. Albedo of deep fresh snow, surface roughness and density of fresh snow were set, respectively, to 0.75, 0.24 cm and 150 kg m^{-3}.

The validation data represent daily snow depth values measured at 24 snow depth observation sites within the French Alps. Of course, there is a scale problem in comparing a point measurement with a simulated value, which represents an average value over an 8 km × 8 km grid cell. To reduce to some extent this inconsistency, the snow sites were thoroughly selected "using criteria based on quality control, and by only considering stations with an elevation difference between the site and the grid-cell mean altitude of 250 m or less” (Boone *et al.*, 2004, p. 191). This allows one to expect that observations are more or less representative and, in general, can be used to evaluate how the model simulates evolution of snow depth and snow ablation during spring snow melt.

Pan-Arctic river basins Two river basins, located in the northeast of the European part of Russia, were chosen for investigation: the Pechora River basin (area: 312 000 km^2) and the Northern (Severnaya) Dvina River basin (area: 348 000 km^2). The basins represent flat forested plains. Forests (with a predominance of coniferous species) cover nearly 80% of the area of each basin.

The climate in the study region is characterized by a short (3–4 months) cool summer and long (5–7 months) cold winter with a stable snow cover and soil freezing. There is permafrost in some areas. Nearly 30–40% of precipitation falls as snow. The streamflow of each river can be mainly characterized as snowmelt (up to 50–80%) and rain driven.

For modelling purposes, the Pechora River basin (from the head of the river down to the Oksino gauging station) was presented by 57 1°×1° computational grid cells in accordance with a global river channel network TRIP (Oki *et al.*, 1999) and the Northern Dvina River basin (down to the Ust-Pinega gauging station) by 62 one-degree grid cells (Fig. 2) (Gusev *et al.*, 2010, 2011).

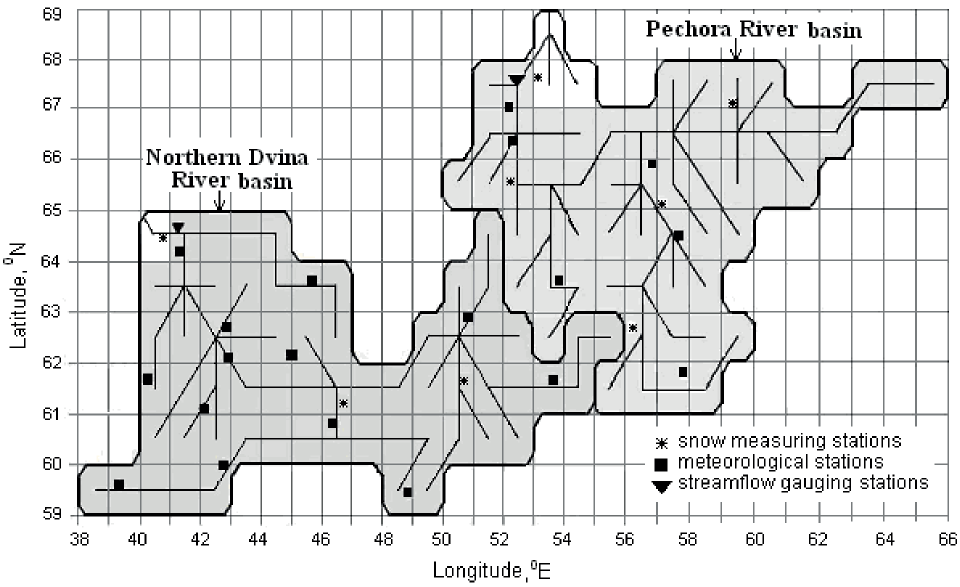

Fig. 2 Schematization of the Pechora River basin and the Northern Dvina River basin.

Meteorological forcing data were derived from observations performed at meteorological stations located within the basins (Fig. 2), as described in Gusev *et al.* (2008, 2010, 2011).

Soil and vegetation parameters were prepared using global one-degree datasets provided within the framework of GSWP-2 (Dirmeyer *et al.*, 2002) as described in Gusev *et al.* (2006). Global one-degree vegetation datasets contain information on the land surface types in accordance with the IGBP classification, which includes 17 types of land surface, and their fractions within each one-degree grid cell, as well as monthly values of biophysical parameters (leaf area index, greenness fraction, roughness length, zero-plane displacement height, snow-free albedo, root depth). Global one-degree soil datasets include data on sand, clay, silt and organic matter fractions; texture classes (12 soil texture classes according to the classification of USDA); depth of active soil column and soil hydrophysical parameters (porosity, field capacity, wilting point, hydraulic conductivity at saturation, saturated matric potential, B-exponent parameter, soil snow-free albedo) for each grid cell.

The required topographic characteristics include mean elevation of grid cells, taken from the EROS Data Centre (EDC), and the slopes of the surface of each cell in the meridianal and latitudinal directions, derived from mean elevations of neighbouring grid cells.

Since soil and vegetation parameters derived from the global datasets are rather rough, some parameters influencing runoff generation to the most extent were calibrated against measured river runoff for the five year period (1986–1990) using the SCE-UA optimization technique (Duan *et al.*, 1992). The choice of calibrated parameters was justified in Gusev *et al.* (2008).

The validation data represent daily river runoff measured at basin outlets and daily snow depth measured at several stations.

RESULTS

Model performance was evaluated using the following goodness-of-fit statistics: the mean difference between the simulated and observed variables (bias), the root-mean-square error (RMSE), the coefficient of correlation *r*, and the Nash-Sutcliffe efficiency *Eff* (Nash & Sutcliffe, 1970).

Snow depth simulations in French Alps Model simulations (without calibration of model parameters) were performed from 1 August 1985 to 31 July 1989. The start and end times were chosen to be during the summertime to make initialization of snow cover and soil freezing easier. The first year was used for model spin-up and its results were not included in further analysis. The observed snow depth values were taken from materials provided by the Rhone-AGG project organizers at the Rhone-AGG Workshop (Toulouse, France, 5–7 November, 2001). Some results of simulation of snow depth dynamics compared to observations are shown in Fig. 3.

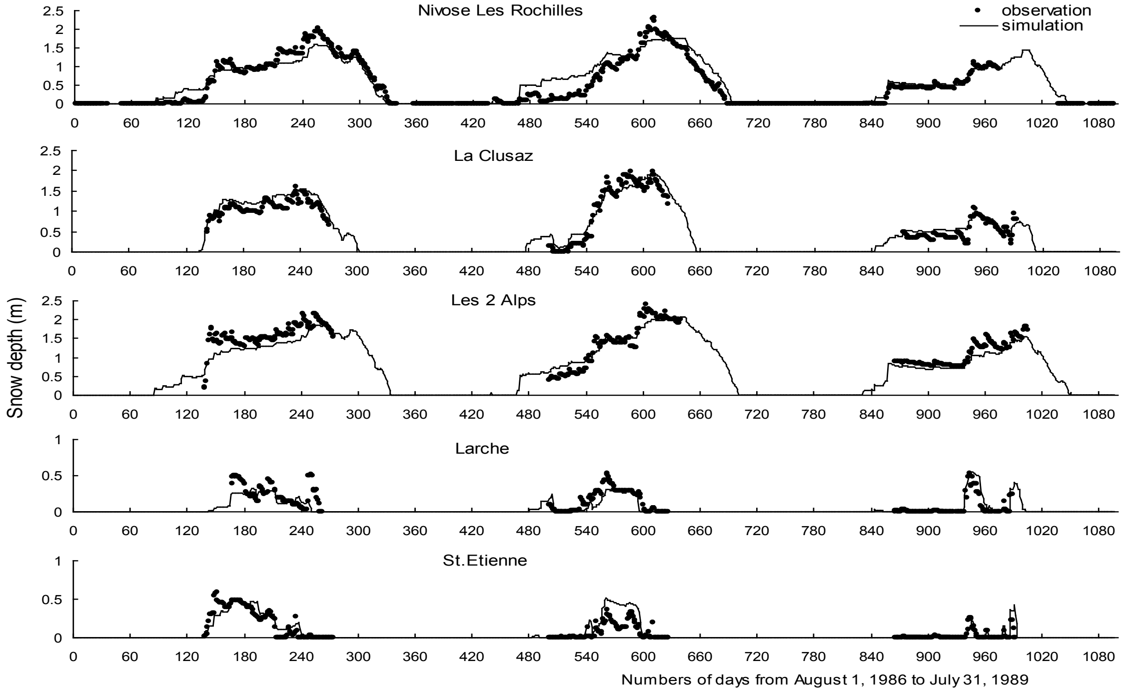

Fig. 3 Dynamics of simulated and observed snow depth at several sites in the French Alps.

The first two panels in Fig. 3 correspond to the best results (in terms of *Eff* and *r*). The third panel corresponds to the largest observed mean snow depth among the sites and the last two panels to the lowest snow depths. As mentioned in Boone *et al.* (2004), most observations cease at the end of April at the closure of ski resorts, and after April, the observations correspond to a single high-altitude (2450 m) research site (Nivose Les Rochilles at the upper panel in Fig. 3). As can be seen, SWAP is able to adequately simulate snow accumulation and ablation, both in the case of high and low snow.

The median value of *Eff* for 24 sites is 0.56. At five sites *Eff* ≥ 0.8, at 16 sites *Eff* > 0.5, and only at three sites *Eff* < 0. On average, the bias equals 0.016 m for 24 sites, that is 2.4% of the mean observed snow depth (equalled to 0.68 m). In most cases, the absolute value of bias does not exceed 0.2 m, its median is 0.11 m. The values of RMSE vary from 0.11 to 0.54 m, while the median value equals 0.23 m. The coefficient of correlation is within the range of 0.62–0.96, its median is 0.88. These results mean that in general SWAP performs statistically fairly well.

It is of great interest and importance to evaluate how the model simulates the maximum snow depth (MSD). Averaged over a 3-year period and for 24 sites, simulated MSD_{sim} is 1.14 m, compared to observed MSD_{obs} = 1.31 m, i.e SWAP underestimates MSD by 13%. RMSE is 0.34 m, *Eff* = 0.72 and *r* = 0.89.

Snow and runoff simulations in pan-Arctic river basins Model simulations were performed from 1 July 1966 to 31 December 1999 for the Northern Dvina River and to 31 December 2000 for the Pechora River. In both cases, the optimized model parameters were applied. The first year was used for model spin-up.

Model validation was performed against streamflow measured during 32 years (1967–1998) at the Ust-Pinega streamflow gauging station (the Northern Dvina River) and during 19 years (1981–1998, 2000) at the Oksino station (the Pechora River). In the former case, bias = 1%, *Eff* = 0.83, *r* = 0.91, while in the latter case, bias = –11.9%, *Eff* = 0.79, *r* = 0.89. Larger bias in the latter case could result from the poorer network of meteorological stations. As can be seen from Fig. 2, the eastern part of the Pechora basin is not covered with meteorological observations.

The dynamics of basin-averaged daily snow depth simulated by SWAP for both rivers is depicted in Fig. 4. Measured daily values of snow depth, also given in Fig. 4, were obtained by averaging over five stations for the Pechora basin and over three stations for the Northern Dvina basin. In the former case, bias = 0.035 m (13.6%), RMSE = 0.07 m, *Eff* = 0.93, *r* = 0.98; in the latter case, bias = 0.034 m (18.8%), RMSE = 0.08 m, *Eff* = 0.87, *r* = 0.96.

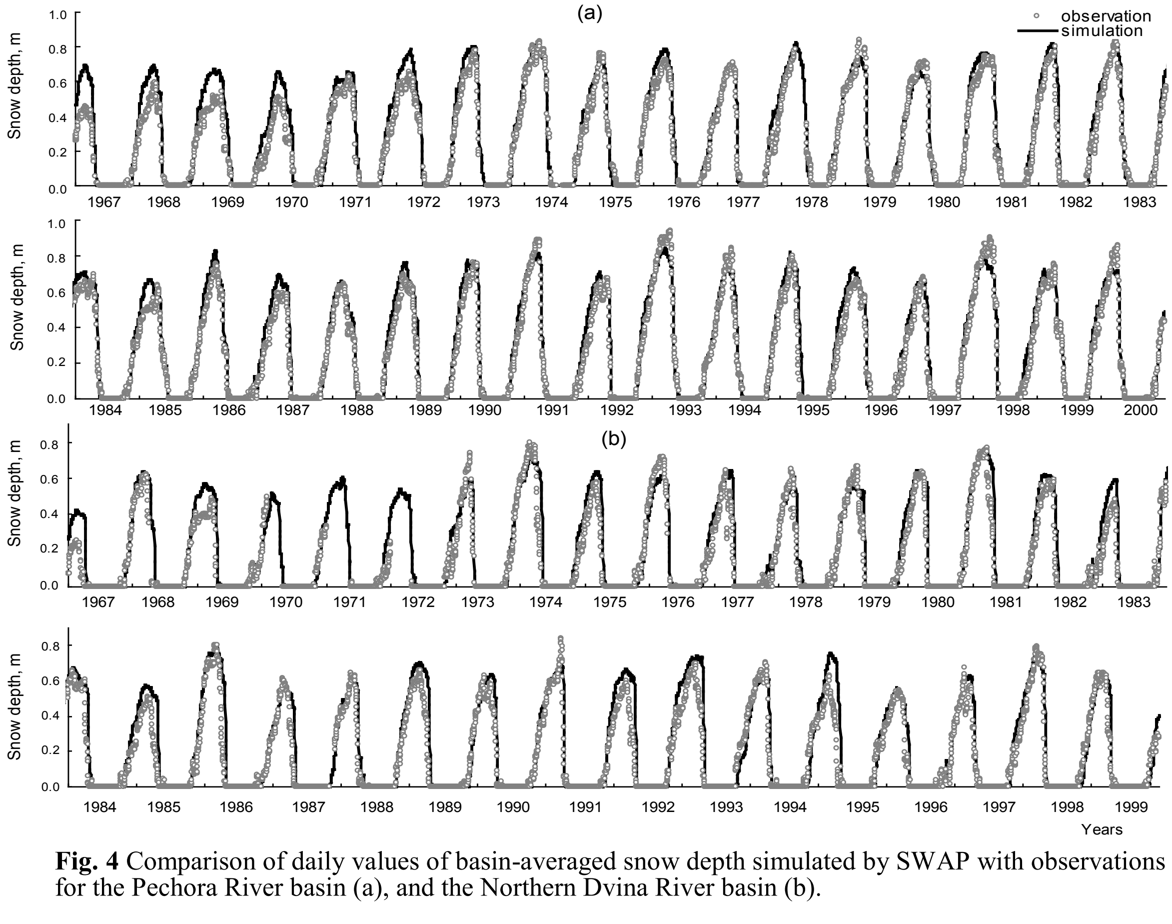

Fig. 4 Comparison of daily values of basin-averaged snow depth simulated by SWAP with observations for the Pechora River basin (a), and the Northern Dvina River basin (b).

CONCLUDING REMARKS

From the results described above, it is possible to see that the land surface model SWAP is able to reproduce the evolution of snow depth in the French Alps as well as the evolution of both streamflow and snow depth for pan-Arctic river basins located in the northeast of the European part of Russia. In general, SWAP performs fairly well statistically.

There are several snow observation sites in the French Alps for which the agreement between observations and simulations is rather poor. The possible reasons may be: (a) a mismatch between the scale of observation and the scale of model application; (b) uncertainties in forcing data, especially in precipitation and incoming radiation, which are inevitable in a mountainous domain with a complex relief; (c) uncertainties in model parameters; and (d) shortcomings of the model.

As to pan-Arctic river basins, we realize that three or five snow measuring stations are not enough for estimating basin-average snow depth. However, at the moment there is no reliable alternative to *in situ* snow observations in the region under study. The accuracy of remote sensing snow measurements is low here, mainly due to the effect of forests. At the same time it is shown that SWAP reproduces streamflow of the northern rivers quite adequately, which would not be possible without adequate simulation of snow formation processes.

All the above allows us to conclude that SWAP behaves reasonably well in mountain and cold domains and can be used for hydrological projections in these regions.

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