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Modelling snowpack formation processes and meltwater runoff using the LSM SWAP under permafrost and highland conditions

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Abstract An ability of a physically-based land surface model SWAP, which describes heat and water exchange processes in a soil–vegetation–(snow cover)–atmosphere system, to reproduce snow formation processes and meltwater runoff at small watersheds under permafrost and highland conditions is investigated. Model simulations were performed for a 10-year period (1969–1978) using observations from the Kolyma Water Balance Station (KWBS), located within the permafrost zone of the Kontaktovyi Creek basin (the upper course of the Kolyma River, Russia). The model was validated against available observations of snow depth; soil thawing/freezing depth; soil and snow surface temperatures; snow evaporation; runoff from different river basins located within the KWBS. The validation results demonstrated the ability of the SWAP model to reproduce heat and water exchange processes under permafrost and highland conditions quite reasonable.
Key words land surface model SWAP; snow formation; meltwater runoff; parameter optimization; Russia

INTRODUCTION

Currently the implementation of land surface models (LSMs) is moving towards high latitudes and high mountainous regions, which are characterized by severe climatic conditions with a long cold season, seasonal or permanent snow cover or ice. Many of these regions are within the permafrost zone and the modelling community is faced with the need to simulate the processes of heat and water exchange between the land surface and the atmosphere under permafrost conditions. Besides that, these regions are usually poorly provided with data required for simulations. These circumstances sufficiently complicate both modelling heat and water exchange processes occurring in the mentioned regions and validation of the developed models. In this connection, the goals of the present work are to investigate the ability of a physically-based land surface model SWAP (Soil Water–Atmosphere–Plants), developed previously by the authors, to simulate (1) snowpack formation processes, and (2) snowmelt and rain driven streamflow under permafrost and highland conditions. These goals were also motivated by the fact that the SWAP model is to be used as an instrument for scenario forecasting the dynamics of hydrological processes due to possible climate change.

LAND SURFACE MODEL SWAP

The land surface model SWAP represents a physically-based model describing the processes of heat and water exchange within a soil–vegetation/snow cover–atmosphere system (SVAS). Model SWAP treats the following processes: interception of liquid and solid precipitation by vegetation; evaporation, melting and freezing of intercepted precipitation, including refreezing of melt water; snow formation processes (including accumulation of snow with its partitioning between solid and liquid fractions, snow evaporation/sublimation and melting, freezing of water in snowpack, snow compression, formation of water yield from snow); surface and subsurface runoff; water infiltration into a soil; soil moisture dynamics affected by transpiration, soil evaporation, water exchange with underneath layers; water table dynamics; formation of the heat balance and thermal regime of SVAS; soil freezing and thawing. The model can be applied both for point (or grid box) simulations of vertical fluxes and state variables of SVAS in atmospheric science applications (Gusev & Nasonova, 1998, 2004; Gusev *et al.,* 2004) and for simulating streamflow at different scales – from small catchments to continental-scale river basins located under different natural conditions (Gusev & Nasonova, 2000, 2002, 2003; Boone *et al.*, 2004; Gusev *et al.*, 2006;

Nasonova *et al.*, 2009). The main elements of SWAP and the results of its validation were described in a series of publications (e.g. Gusev & Nasonova, 1998, 2002, 2003, 2010).

STUDY BASIN AND ITS SCHEMATIZATION

The Kontaktovyi Creek basin (area: 21.2 km^2) represents a highland located in the upper course of the Kolyma River (61°53′N, 147°43′E, the Far East of Russia) in the permafrost zone. This is an experimental basin of the Kolyma Water Balance Station (KWBS). The absolute heights within the basin vary from 830 to 1700 m a.m.s.l. The climate of the region is subarctic continental. During the period 1969–1978 mean annual air temperature was negative (–11°C), while mean daily temperature varied from –52 to 23°C. Annual precipitation varied within a basin from 300 to 460 mm. The depth of seasonal soil thawing ranged from 0.3–0.4 to 1.5–2 m, depending on slope exposition, lithological composition of ground, vegetation and air temperature. Vegetation consists of sparse larch forest, low creeping cedar, moss and grass. The upper parts of slopes are presented by rock debris.

For the simulation of streamflow, the Kontaktovyi Creek basin was divided into five sub-basins (Fig. 1). In its turn, for the 1st, 2nd and 5th sub-basins, the slopes of southern and northern aspects were treated separately because of different natural conditions. More detailed division of the basin seems to be unreasonable because of the lack of reliable data. Three types of the land surface were distinguished within each model element: sparse larch forest growing below 1000 m, low creeping cedar and bare areas represented by talus. Model simulations were performed for each land surface type, then streamflow for each sub-basin was calculated as a weighted average value accounting for the spatial coverage of each land surface type. Two small catchments (Morozova Creek and Yuzhnyi Creek) were chosen for parameters calibration (Fig. 1).

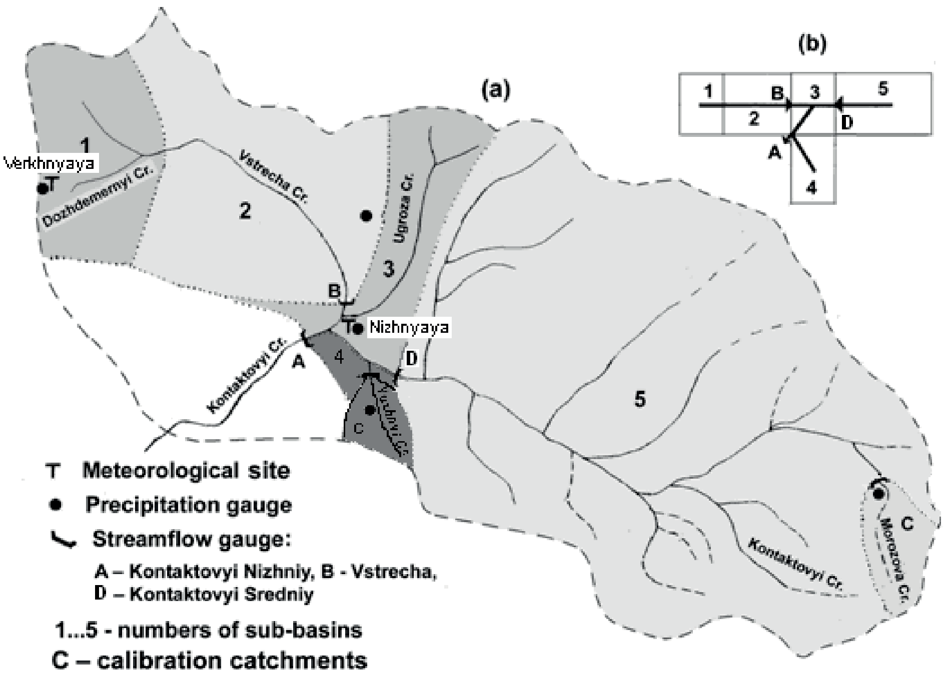

Fig. 1 Schematic representation of the Kontaktovyi Creek basin divided into 5 sub-basins, streamflow evaluation sites (A, B, D) and location of the two calibration catchments (a); schematized routing directions (b).

DATA

Meteorological data

The model requires the following forcing data: air temperature and humidity, atmospheric precipitation, wind speed, air pressure and incoming short- and longwave radiation. All the forcing data, with the exception of radiation, were measured at the Nizhnyaya (1969–1978) and Verkhnyaya (1969–1972) meteorological sites located at 850 and 1220 m a.m.s.l., respectively (Fig. 1); their daily values are given in Kolymskoye UGKS (1977). Meteorological measurements (with the exception of precipitation) from the Nizhnyaya site were adjusted to mean elevation of each calculational element (using, in addition, the data from the Verkhnyaya site and accounting for the difference in the elevation of these two sites). Precipitation gauges were also located within each small experimental catchment (Fig. 1) where measurements were performed daily during the warm season (May–September). During the cold season, precipitation measurements were carried out only at the Yuzhnyi and Severnyi Creek catchments (once in a 10-day period). For model simulations, daily precipitation was restored for each catchment and then uniformly adjusted to 3-h time steps. Incoming short- and longwave radiation values for each calculational element were estimated on the basis of meteorological data (with accounting for cloudiness, latitude, solar declination, view factor, average slope in meridional and latitudinal directions, and mean monthly values of atmospheric transparency). For estimation of incoming longwave radiation we used empirical formulae derived by ourselves for similar severe climatic conditions (for details, see Gusev *et al.*, 2006).

Model parameters

Application of the SWAP model requires soil and vegetation parameters. Soil parameters include field capacity W_{fc}, wilting point W_{wp}, soil porosity W_{sat}, and dependences of soil hydraulic conductivity k and soil matric potential ϕ on soil moisture W, i.e. $k(W)$ and $\phi(W)$. In SWAP, Clapp & Hornberger (1978) parameterizations for $k(W)$ and $\phi(W)$ are used. These parameterizations require information on soil matric potential at saturation, ϕ_0, B-parameter, W_{sat}, and saturated hydraulic conductivity k_0. In addition, snow-free albedo of bare soil α_{soil} and soil depth h_{soil} are also required. As to vegetation parameters, SWAP needs root depth h_{root}, leaf and stem area indexes (LAI and SAI, respectively), roughness length of vegetation, zero plane displacement height, snow-free albedo of vegetation, albedo of vegetation with intercepted snow on crowns, effective linear leaf size, interception capacity of vegetation for liquid and solid precipitation. Since these parameters were not available for the selected basins, we had to estimate them.

A priori estimation of soil and vegetation parameters was based on qualitative description of soil and vegetation types and their spatial distribution within the Kontaktovyi Creek basin (see Gusev *et al.*, 2006 for details). To improve runoff simulations based on *a priori* parameters, six key-parameters (W_{fc}, W_{wp}, W_{sat}, k_0, h_{soil}, h_{root}) were optimized by means of model calibration by minimization of root-mean-square-deviation (*RMSD*) between simulated and measured (during 1969–1978) daily total runoff from the two calibration catchments (Morozova Creek and Yuzhnyi Creek). Four parameters (W_{fc}, W_{wp}, W_{sat}, k_0) were optimized for two soil layers and each parameter was calibrated for three land surface types. The model calibration was performed by means of automatic procedures for optimization based on stochastic or Monte-Carlo techniques.

Validation data

The validation data represented snow depth (measured by three permanent snow measurement rods); soil thawing/freezing depth (derived from measurements of soil temperature at different depths down to 3.2 m); daily soil and snow surface temperatures; snow evaporation (measured by evaporometer GGI-500-6 with an area of 500 cm^2 and a height of 6 cm); and daily runoff from different catchments and river basins located within the KWBS.

RESULTS

Model simulations were conducted for the period 1969–1978 using daily meteorological data from the KWBS. Here, we can only briefly describe the most interesting results. First of all, model validation was performed using different measurements obtained at the Nizhnyaya site. Figure 2 illustrates how SWAP reproduces snow formation processes and soil thawing/freezing in the permafrost zone. As can be seen from Fig. 2(a), modelled snow depth formed by the beginning of spring snowmelt is in a good agreement with measurements, the processes of spring snowmelt and soil thawing (after the end of melting) are also adequately reproduced. As to evaporation from the snowpack (Fig. 2(b)), a good agreement with observations cannot be expected because of great uncertainties in the input data (in particular, in the estimates of incoming longwave radiation) and small values of snow evaporation rate E_{sn}. It can only be noted that the modelled rates are within the range of the observed ones. During the night time, condensation usually took place, while during the day time evaporation dominated. In general, SWAP tends to overestimate E_{sn} during the night and to underestimate it during the day time.

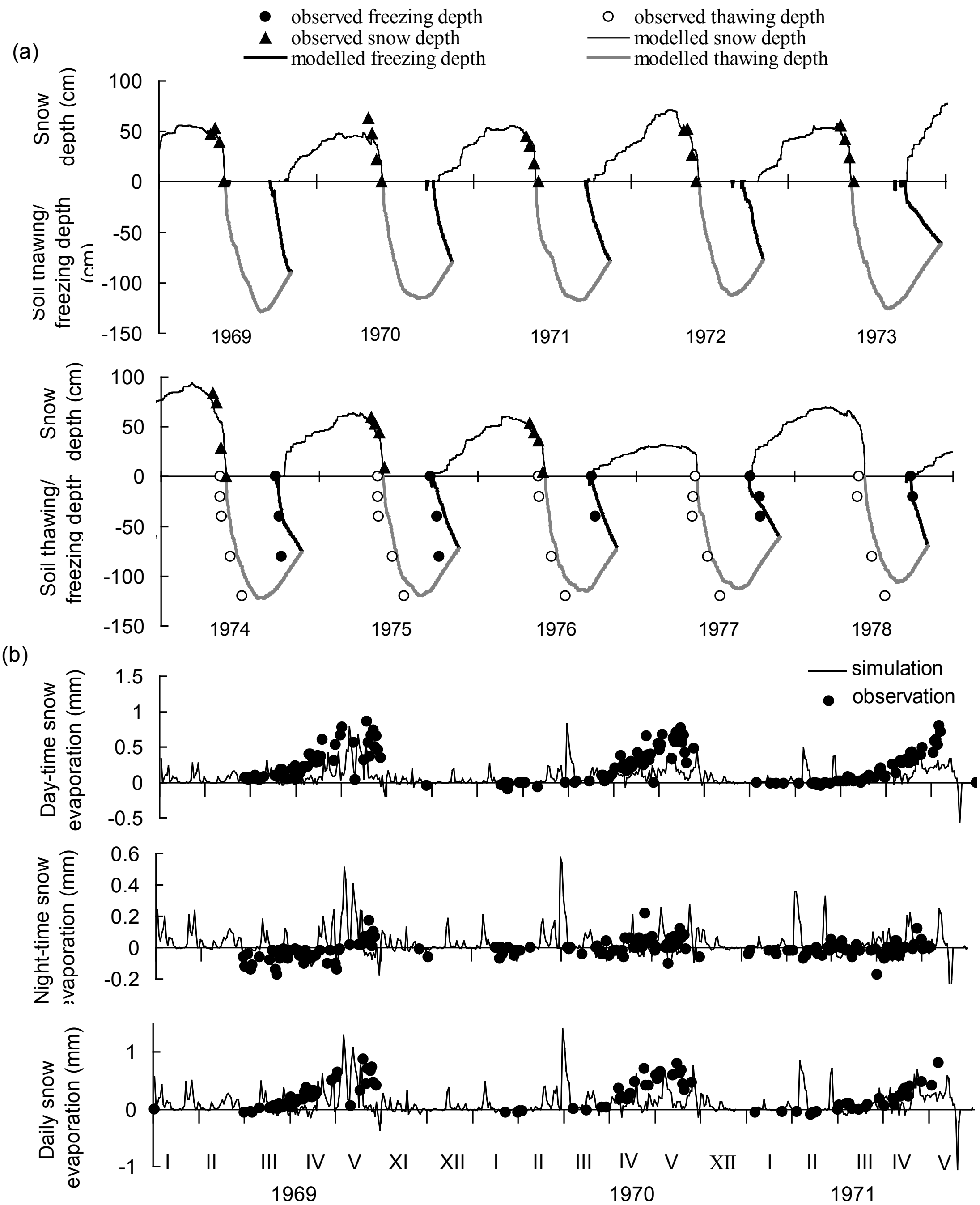

Fig. 2 Dynamics of modelled and measured (at the Nizhnyaya site) (a) soil thawing/freezing depths and snow depth; (b) daily, day-time and night-time snow evaporation.

The ability of SWAP to simulate daily snow surface temperature t_{sn} is shown in Fig. 3 for three cold seasons. Measured t_{sn} varied from 0 to –61°C during 1969–1978, while simulated values dropped down to –58°C. Good agreement between measured and modelled temperature is confirmed by statistics obtained for the 10-year period (2353 days). Thus, mean observed $t_{sn,obs}$ was –25.4°C against mean modelled $t_{sn,mod}$ = –26.9°C, i.e. bias equalled to –1.5°C, root-mean-square deviation RMSD = 2.8°C, Nash-Sutcliffe efficiency (Nash & Sutcliffe, 1970) *Eff* = 0.96, the coefficient of correlation *r* was 0.99. The obtained bias seems to be acceptable taking into account that the accuracy of measured data was 0.5°C.

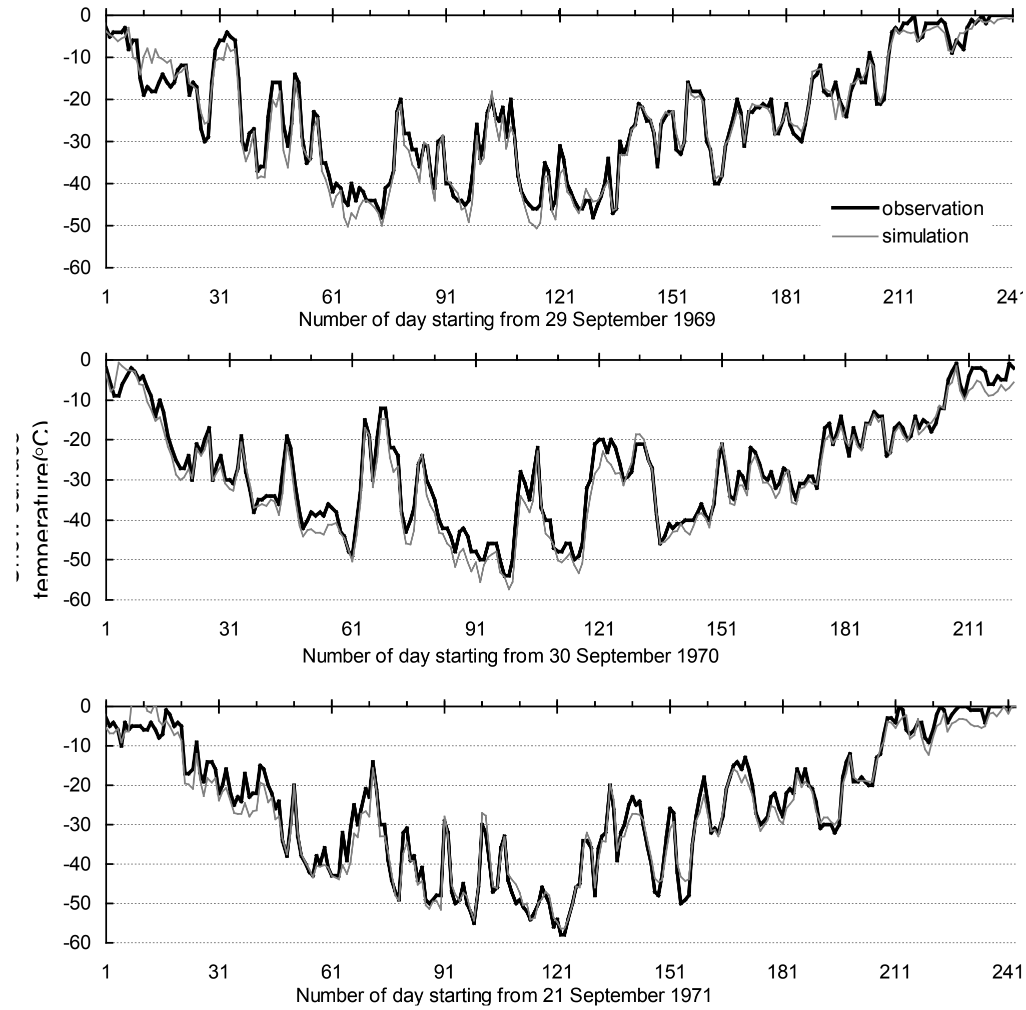

Fig. 3 Modelled and measured daily temperature of snow surface for three cold seasons at the Nizhnyaya site.

Streamflow simulations were performed for several watersheds and sub-basins (with an area ranging from 0.27 to 21.2 km^2) of the Kontaktovyi Creek basin (Fig. 1). In general, the agreement between daily streamflow simulations and observations is not quite satisfactory. The Nash-Sutcliffe efficiency varied among the basins from 0.45 to 0.64, the coefficient of correlation ranged from 0.72 to 0.81, the bias was between –3 and –20% (i.e. streamflow was underestimated). For the whole basin, *Eff* = 0.64, RMSE = 1.1 mm/day, *r* = 0.81 and bias was –11%; comparison of simulated and observed hydrographs is shown in Fig. 4. Less good agreement seems to be associated mainly with poor precipitation measurements. First, measured precipitation is usually underestimated due to wind (especially during the cold season which lasts up to 7 months in the region under study). According to the climatic data, such an underestimation may reach as much as 14–25% in the given region. This is comparable with our results. Secondly, as mentioned above, for most of the basin precipitation values during the cold season were restored. Thirdly, adjustment of daily precipitation to 3-h time steps also contributes to underestimation of streamflow during the warm season when rainstorms occur. In addition, inaccuracy of estimated incoming radiation may also influence the results.

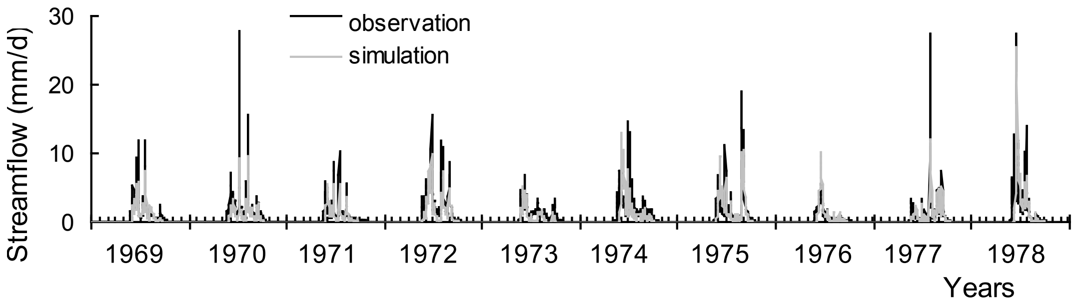

Fig.4 Modelled and measured hydrographs of daily streamflow from the Kontaktovyi Creek basin.

Taking into account the large uncertainties in forcing data and model parameters, in general, the results obtained can be considered as satisfactory and we can conclude that the LSM SWAP is able to reproduce snow formation and runoff generation processes under permafrost and highland conditions reasonably well.

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