

## **Application of a land surface model for studying the role of boreal spruce forest in land surface–atmosphere interactions**

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**Abstract** The aim of this paper is to study the impact of boreal spruce forest on heat and water exchange between the land surface and the atmosphere by means of an advanced land surface model SWAP, which adequately treats the energy balance and hydrology of boreal forests and non-forested areas. The work is based on model results and observations obtained during 18 years (1966–1983) at the Tayozhniy catchment (covered by boreal forest, mainly composed of spruce) and the Usadievskiy catchment (grassland), both situated in the central part of the Valdai Hills, Russia. The results of model simulations for the forested and non-forested catchments were compared to reveal the role of the spruce forest in land surface–atmosphere interactions. The main emphasis was on the cold season processes, since these have received less attention in land surface modelling.

**Key words** boreal spruce forest; land surface model; water balance components

### **INTRODUCTION**

Boreal forests represent a large biome which occupies nearly 15% of the land surface (Pomeroy & Dion, 1996); 73% of them are located in Russia (Pisarenko, 1998). It is evident that boreal forests influence the heat and water exchange between the land surface and the atmosphere. An effective tool for studying this impact may be an advanced land surface model (LSM) that adequately treats the energy balance and hydrology of the boreal forests. Since boreal forests are situated in high latitudes with cold climate, characterized by a clear seasonal course of hydrometeorological conditions, deep snow cover, seasonally frozen soil or permafrost, the LSM should adequately treat cold season processes. Here, a physically-based LSM SWAP (soil water–atmosphere–plants) model is used, which has been developed and successfully validated (against a vast number of heat and water balance components measured in the boreal spruce forest and non-forested areas on a long-term basis) by the authors (e.g. Gusev & Nasonova, 1998, 2000, 2001).

### **MODEL**

The latest version of the land surface model SWAP (Gusev & Nasonova, 2001) explicitly accounts for the following processes: partitioning of rainfall and snowfall between interception by the canopy (in so doing, snow interception is distinguished from

rain interception) and falling to the ground, evaporation of intercepted rainfall, formation of snow cover on the forest crown and forest floor (or in the open site) including snow accumulation (both in solid and liquid fractions), snow evaporation and snowmelt, transpiration, soil evaporation, water infiltration into frozen/unfrozen soil, dynamics of frozen and unfrozen water in a soil, surface runoff, drainage from frozen/unfrozen soil, formation of the surface energy balance, and soil freezing/thawing processes.

The latest version of SWAP (Gusev & Nasonova, 2001) was validated against a vast set of intensive observations obtained by the Valdai Scientific-Research Hydrological Laboratory (VSRHL) during 18 years (1966–1983) at different experimental catchments. These catchments are located at the central part of the Valdai Hills, Russia (57.6°N, 33.1°E) in a boreal forest region with a moderate climate characterized by a clear seasonal course of hydrometeorological conditions, deep snow cover, seasonally frozen soil, and complicated hydrological regime. Simulations of different characteristics of heat and water regime of grassland and forested catchments, in particular, snow density, snow depth, snow water equivalent, daily snow surface temperature, daily evaporation from snow cover, water yield of snow cover, water table depth, depth of soil freezing and thawing, soil water storage in two layers, daily surface and total runoff from the catchment, monthly evapotranspiration from the catchment, and precipitation intercepted by spruce forest on an annual and monthly basis were validated against observations. The results of validation presented in Gusev & Nasonova (2000, 2001) allow us to conclude that the land surface model SWAP parameterizes heat and water exchange processes (including the cold season processes) which occur in a boreal forest region quite reasonably. As such, SWAP can be used as a tool for studying the role of boreal forest in land surface–atmosphere interactions.

## STUDY SITES AND MATERIALS

The sites chosen for the study represent two experimental catchments in the Valdai region: the Usadievskiy catchment (area: 0.36 km<sup>2</sup>) covered mainly with a grassland meadow and the Tayozhniy catchment (area: 0.45 km<sup>2</sup>) covered with a mature boreal forest mainly composed of spruce. The Tayozhniy catchment is 100% forested: mean tree height is 26 m, forest stand age is 85–90 years, closeness of forest crown is up to 0.7, i.e. the spruce forest is rather dense. The type of soil at both catchments is the same—podzol soil; however, soil hydrophysical characteristics are different (see Table 1).

**Table 1** Soil characteristics for the Tayozhniy (spruce forest) and Usadievskiy (grassland) catchments.

Soil properties	Tayozhniy catchment	Usadievskiy catchment
Soil texture (%):		
loam	67	56
sandy loam	30	28
sand	3	16
Soil porosity in top 1 m (m m <sup>-3</sup> )	0.493	0.401
Water content at field capacity in top 1 m (m m <sup>-3</sup> )	0.294	0.271
Water content at wilting point in top 1 m (m m <sup>-3</sup> )	0.124	0.115
Hydraulic conductivity at saturation (m s <sup>-1</sup> )	7 × 10 <sup>-5</sup>	2 × 10 <sup>-5</sup>

A detailed description of the Valdai region with its experimental catchments is given in a number of publications (e.g. Fedorov, 1977; Schlosser *et al.*, 2000). The climate in the region is moderate continental. The mean annual air temperature is 3.1°C, the measured air temperature is within the range from –46.8 to +33.3°C, i.e. the absolute amplitude of temperature variation is equal to 80°C. The mean annual sum of precipitation is about 700 mm. Snow typically covers the surface from November to the end of April. During the cold season the upper soil layer is typically frozen.

The data set for the Usadievskiy catchment was partly provided by the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) Phase 2(d) organizers (Schlosser *et al.*, 2000); the other data were taken from reference books of the VSRHL. The atmospheric forcing data to drive the model and model parameters for the two catchments are detailed in Gusev & Nasonova (2000, 2001).

## RESULTS

The results of model simulations over the period 1966–1983 for the forested (Tayozhniy) and non-forested (Usadievskiy) catchments were compared to reveal the role of the spruce forest in the land surface–atmosphere interactions. Among the processes under consideration, the following processes were simulated by the model:

- partitioning snowfall and rainfall between interception by the canopy and falling to the ground;
- evapotranspiration from the spruce forest and grassland including evaporation (sublimation) of intercepted rainfall (snowfall), sublimation of snow accumulated on the ground, transpiration, soil evaporation;
- formation of snow cover under the spruce crowns and in the open site;
- formation of soil water storage in the forested and non-forested areas;
- runoff from the forested and non-forested catchments.

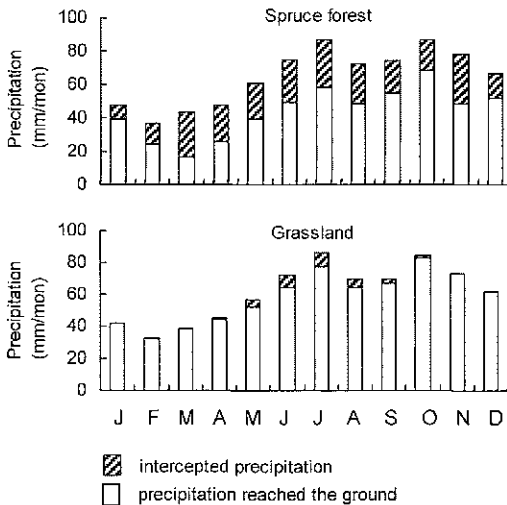
Here, we only consider the more interesting results.

According to model calculations, the mature spruce forest intercepts 28–37% of annual precipitation averaging to 32% over the 18-year period, whereas grassland meadow intercepts 3–6% of annual precipitation (on the average, 4.5%) over the same period (Table 2). Figure 1 shows the annual course of precipitation with the partitioning between interception by various canopies and falling to the ground. It is evident that, in the open site, interception of precipitation is absent during the cold season when the grass is covered by snow. In the spruce forest, as simulated by the model for the study period, 64–84% (on the average, 72% or 181 mm year<sup>-1</sup>) of intercepted precipitation are in a liquid form and 16–36% (on the average, 28% or 69 mm year<sup>-1</sup>) are in a solid form. The ratio between intercepted solid and liquid precipitation for the given forest depends upon the meteorological conditions of a year.

Simulated over the 18-year period, annual evapotranspiration,  $E$ , from the spruce forest is found to be 1.4 times (or 172 mm year<sup>-1</sup>) greater than from the grassland (Table 2). The main contribution (up to 140 mm year<sup>-1</sup>) to this increase is from the greater evaporation of intercepted precipitation,  $E_C$ , from the spruce forest, while the increase in transpiration,  $E_T$ , from the forested area is mainly compensated for by the decrease in soil evaporation,  $E_S$  (Table 2). Snow evaporation under the crowns is greater (by 22 mm year<sup>-1</sup>) than in the open site because of greater net radiation.

**Table 2** Comparison of different simulated hydrological characteristics for forested and non-forested catchments, averaged over the 18-year period (1966–1983).

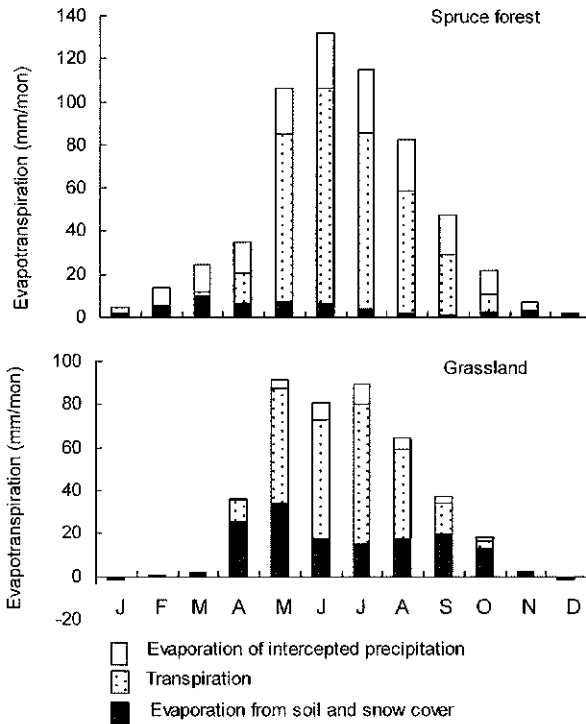
Variable	Tayozhnyi catchment (spruce forest)	Usadievskiy catchment (grassland)	Difference between Tayozhnyi and Usadievskiy catchments
Intercepted precipitation (mm year <sup>-1</sup> ):	250	33	217
rainfall	181	33	148
snowfall	69	-	69
Evapotranspiration (mm year <sup>-1</sup> ):	592	420	172
evaporation of intercepted precipitation	173	33	140
transpiration	367	243	124
soil evaporation	32	145	-113
snow cover evaporation	20	-2	22
Total runoff (mm year <sup>-1</sup> ):	173	306	-133
surface runoff	10	63	-53
ground runoff	163	243	-80
Mean snow depth (cm)	30	35	-5
Maximum snow water equivalent (mm)	148	161	-13

**Fig. 1** Partitioning of precipitation between interception by the canopy and falling to the ground, as simulated by the land surface model SWAP for the Tayozhnyi (spruce forest) and the Usadievskiy (grassland) catchments (averaged over 1966–1983).

Averaged over 18 years, evapotranspiration during the cold season (November–March) is equal to 51 mm in the forest and 2 mm in the open site. In the forest, the main contributors to  $E$  are: evaporation of intercepted precipitation,  $E_C = 27$  mm per season and snow cover evaporation,  $E_{SN} = 17$  mm per season, while  $E_T$  and  $E_S$  are negligible (2.4 and 3.4 mm per season, respectively). Greater evapotranspiration in the forested area can be explained, first of all, by greater net radiation due to the lower albedo of winter spruce forest, compared to the open site. Thus, winter albedo of

evergreen forests with snow on tree crowns rarely exceeds 0.2–0.3, whereas albedo of deep fresh snow in the open site is as much as 0.7–0.9. Moreover, higher vegetation produces greater aerodynamic roughness, which results in more intensive turbulent exchange and, consequently, may enhance evapotranspiration.

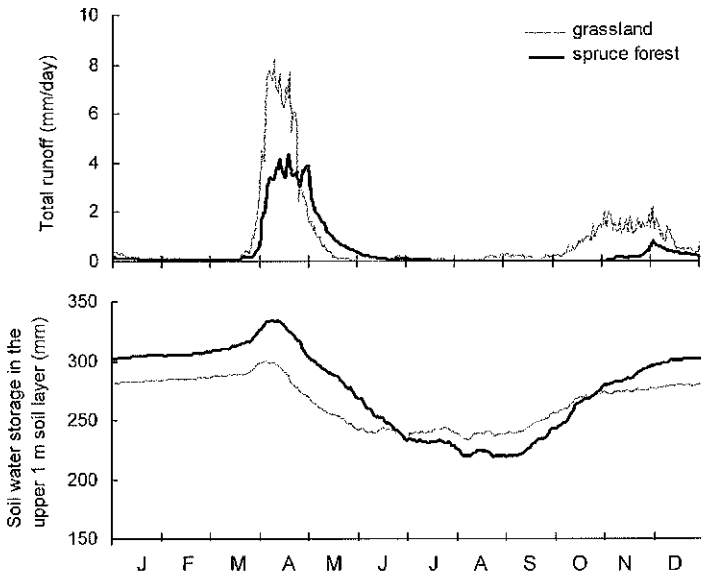
It should also be noted that boreal forest changes the structure of evapotranspiration. Thus, for the spruce forest,  $E_C$  was calculated to be 29% of annual evapotranspiration,  $E_T$ —62%,  $E_S$ —6%, and  $E_{SN}$ —3%. For the open site,  $E_C$  was found to be equal to 8% of annual evapotranspiration,  $E_T$ —58%,  $E_S$ —35%, and  $E_{SN} \approx 0\%$ . Figure 2 shows the differences in the annual course of different components of evapotranspiration for the forested and non-forested areas.



**Fig. 2** The structure of evapotranspiration, as calculated by the model SWAP for the forested and non-forested catchments (averaged over 1966–1983).

Modelled annual total runoff,  $R$ , from the forested catchment varies from 69 to 292 mm year<sup>-1</sup> (average during the period 1966–1983: 172 mm year<sup>-1</sup>). For the grassland catchment,  $R$  ranges from 161 to 449 mm year<sup>-1</sup> (average: 305 mm year<sup>-1</sup> during the same period); i.e. total runoff from the forested catchment is nearly half of that from the non-forested catchment. The average annual runoff ratio equals 0.22 (varying from 0.09 to 0.32) for the forested catchment and 0.42 (ranging between 0.28 and 0.53) for the non-forested catchment.

Figure 3 shows simulated hydrographs for the forested and grassland catchments averaged over the 18-year period. As may be seen, there are two peaks: the highest



**Fig. 3** Total runoff from the Tayozhnyi (forested) and the Usadievskiy (non-forested) catchments and soil water storage in the upper 1 m soil layer under spruce forest and under grass, as calculated by SWAP (averaged over 1966–1983).

peak occurs in spring due to snowmelt and the lower peak is in autumn due to increased rainfall (see Fig. 1) in combination with a decrease in evapotranspiration (see Fig. 2) and high soil moisture status (Fig. 3). The spring peak in the spruce forest is lower and smoother than that in grassland and is shifted in time. This can be explained mainly by (a) differences in snow formation processes which lead to less snow accumulation in the forest (Table 2), and (b) greater infiltration and greater increase in soil water storage during the period of snowmelt in the forest. In the spruce forest, better conditions for infiltration of melted snow are connected with higher soil hydraulic conductivity at saturation, less soil freezing and lower snowmelt rate.

Surface runoff in the grassland catchment results mainly from the spring snowmelt; however, sometimes it can take place in the autumn after heavy rainfall. In the forested catchment, surface runoff is negligible (Table 2): it can occur rarely and only in spring when soil moisture is great.

The results obtained show that the mature spruce forest strongly influences hydrological processes by means of redistribution of incoming heat and water. It should be noted that the results do not contradict *in situ* measurements. This confirms that the advanced land surface model can be used as an effective tool for solving different problems of scientific and practical importance, such as studying the role of boreal forests in land–atmosphere interactions, studying the effect of deforestation or forest regeneration and so on, provided that input meteorological data and model parameter values of high quality are available.

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