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PERMAFROST MONITORING AND PREDICTIONS

HYDROLOGICAL MODELING: SEASONAL THAW DEPTHS IN DIFFERENT LANDSCAPES OF THE KOLYMA WATER BALANCE STATION (*Part 2*)

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Active layer dynamics in highland landscapes within continuous permafrost in northeastern Russia (upper Kolyma River basin) is simulated using the *Hydrograph* distributed hydrological model. The simulations use field data from the Kolyma water balance station (KWBS) grouped into four landscape types, which differ in thermal regime and thaw depths (0.5–1.8 m): rocky talus, alpine tundra, moss-lichen sparse forest, and light forest. The soil properties are systematized and make basis for the classification of soil profiles in the four landscape types with the corresponding sets of model parameters for *Hydrograph*. The active layer dynamics is simulated for seven sites of daily frost/thaw depth measurements (cryopedometry) that differ in types of soil, vegetation and topography. The simulation results agree well with observations for the period of 1950 through 1990 at all sites. Thus, the suggested classification of soil profiles and choice of model parameters are suitable for simulation of active layer dynamics in diverse conditions of the Kolyma station.

Seasonal thaw depth, physical properties of soil, Kolyma water balance station, Hydrograph model

INTRODUCTION

The runoff generation within permafrost has some specificity due to seasonal frost/thaw changes [*Woo et al., 2008*]. Namely, the permafrost heat budget controls the formation of an impermeable frost table, the surface-subsurface flow interactions, as well as the seasonal runoff redistribution upon freezing of rain moisture or meltwater infiltration into frozen soil [*Lebedeva and Semenova, 2012*]. Thus, the active layer dynamics has to make part of hydrological modeling for permafrost basins.

Estimating thaw/frost depth without reference to moisture flow in soils [*Sosnovsky, 2006; Malevsky-Malevich et al., 2007*] appears to be a wrong approach in the case of hydrological modeling. Current methods to simulate thaw/frost depth differ in algorithms and parameterizations, and can be analytical, numerical, empirical or semi-empirical [*Zhang et al., 2008*]. The empirical methods, in which thaw depth is proportional to the quadratic function of the snow melting time require calibration and account neither for soil physics nor for the past and present freezing and moisture flows (e.g., the *TopoFlow* [*Schramm et al., 2007*] and the *ARHYTHM* Arctic hydrological and thermal [*Zhang et al., 2000*] models).

Semi-empirical heat budget assessment assumes heat flux between soil layers to be proportional to their temperature difference and thermal conductivity. It focuses mainly on surface temperature calculations with reference to incoming long- and short-wavelength radiation, albedo, etc. The changing states of soil are included via empirical thermal conductivity difference between wet (frozen) and dry soils. The SWAP (Soil – Water – Atmosphere – Plants) model tested with data of the Kolyma Water Balance Station (KWBS) [*Gusev and Nasonova, 2010*] solves the thermal conductivity equation for freezing/thawing soil by coupling energy and water flow components. However, the use of the approach for permafrost areas is problematic because it requires calibration of multiple model parameters and large sets of input meteorological data for calculating the soil-vegetation heat budget.

Numerical simulations imply finite-difference or finite-element solutions to the 1D thermal conductivity equation [*Sosnovsky, 2006; Arzhanov et al., 2007; Malevsky-Malevich et al., 2007; Pavlova et al., 2007*]. For instance, thus found thermal conductivity is used by *Kuchment et al.* [*2000*] to estimate thaw depth at a site within KWBS (presumably No. 12) and to simulate the runoff, but the model neglects spatial variations of soil and vegetation over the basin: the respective parameters are assumed constant for the whole 99 400 km^2 Kolyma catchment.

Simulation of permafrost and seasonal thaw depth often uses coupled heat and water flow (Richards) equations. However, modeling seasonal thaw patterns, especially for hydrological applications, requires high spatial resolution. The results of active layer thickness simulations with the JULES land surface scheme on a 0.5 × 0.5° grid reported by *Dankers et al.* [*2011*] are generally satisfactory but fail to account for sub-grid variability. Such simulation results differ considerably from measured data from Russia even in annual means within depths of 0 to 3 m.

Better spatial resolution is provided by distributed hydrological models, such as *GEOtop* [*Rigon et al., 2006*], in which the 1D thermal conductivity and Richards equations that represent coupled energy and water budgets, respectively, are solved jointly on grids from a few meters to a few tens of meters, with time intervals from minutes to hours. However, the method is computationally expensive and difficult to apply to medium and large basins, even with the advanced computing facilities. Moreover, this high-resolution modeling fails to faithfully reconstruct thaw variability in small basins as well (e.g., a notable difference between simulated and measured weekly mean thaw depths was reported for a small basin in Canada [*Endrizzi et al., 2011*]).

To avoid distorting or overlooking some important effects, which is inevitable with grid cell averaging of soil and vegetation properties, we suggest, instead, to use data points representative of typical landscapes and slope conditions [*Vinogradov, 1988*].

The active layer simulations of this study use data from seven sites of frost/thaw depth measurements within the Kolyma water balance station located in different landscapes of continuous alpine permafrost. Data from the seven cryopedometers placed in river valleys, on watersheds and on hill slopes that differ in types of soil and vegetation make reference in analysis of moisture and heat patterns, estimating the parameters of the hydrological model, and simulating seasonal thaw depths.

Thermal conductivity and heat transfer are computed using algorithms designed for hydrological modeling and integrated into the *Hydrograph* deterministic model [*Vinogradov, 1988; Vinogradov et al., 2011; Semenova et al., 2013*]. The model simulates all processes in the surface runoff cycle and is applicable to the basins of northern rivers. It includes explicitly the algorithms for estimating heat and water flows in a soil profile with model parameters according to the observed properties of soil and vegetation. *Hydrograph* works well even in the case of poorly gauged basins as it requires only few input meteorological variables (temperature and humidity of air and precipitation).

The differential equation of soil thermal conductivity is simplified and allows an algebraic solution. The ground temperatures are averaged over the model time step instead of being continuous in neighbor soil layers; they are constant at any point of a simulated layer, like all other physical properties, but change abruptly across layer boundaries. The *Hydrograph* model was applied in Part 1 of our study to simulate heat dynamics in the system "Atmosphere–Snow–Soil", with phase transitions [*Vinogradov et al., 2015*].

ACTIVE LAYER CONDITIONS IN THE KWBS AREA

The Kolyma water balance station lies over 22 km^2 in northeastern Russia in the Kulu basin, a right tributary of the upper Kolyma River. The station is a unique natural laboratory where highland continuous permafrost has been monitored for almost seventy years (Fig. 1). The elevation in the area varies from 830 to 1600 m a.s.l. and the slope locally reaches 40°. The mean annual air temperature at the Nizhnyaya (Lower) site is –11.4 °C (over 1948–1995) [*Sushchansky, 2002*] and the precipitation is from 290 to 460 mm (1959–1990) depending on the slope height and aspect.

Diverse hydrometeorological observations have been run at KWBS since 1948 [*Observation Reports, 1959–1991*], including frost/thaw depth (active layer thickness) measurements with cryopedometers designed by Danilin [*National Standard, 1981*]. The thawing/freezing patterns at KWBS depend on soil and vegetation types, elevation, and slope parameters, all highly variable within quite a small area of the station. These factors, combined in different ways, represent several landscapes: rocky talus and alpine tundra at hill tops and on watersheds (over 35 % of the area); south-facing slopes with dwarf Siberian pine (~26 %); north-facing slopes with sparse larch forests (12 %) and creek valleys with a thick moss-lichen cover (27 %) [*Pugachev, 2002*].

The active layer at KWBS behaves in three different ways.

In sparse forests with a moss-lichen floor growing on north-facing slopes and in swampy creek valleys, meltwater immediately flows down to the frost table. Most of it infiltrates into soil, freezes up and then melts back upon soil thawing. The thaw depth is shallow (0.5–0.7 m) because sphagnum and lichen provide heat insulation while the ice-rich soil is poorly permeable [*Boyarintsev, 1988*]. The summer thaw of this soil supplies moisture to moss independently of rainfall.

Talus on watersheds and hill tops has low moisture holding capacity and lets meltwater flow freely into frozen soil which spends almost all cold it stores on pore water freezing. The maximum possible ice content reaches 5 % occupying ~15 % of the pore space at 0.35 porosity [*Bantsekina, 2003*]. By the time

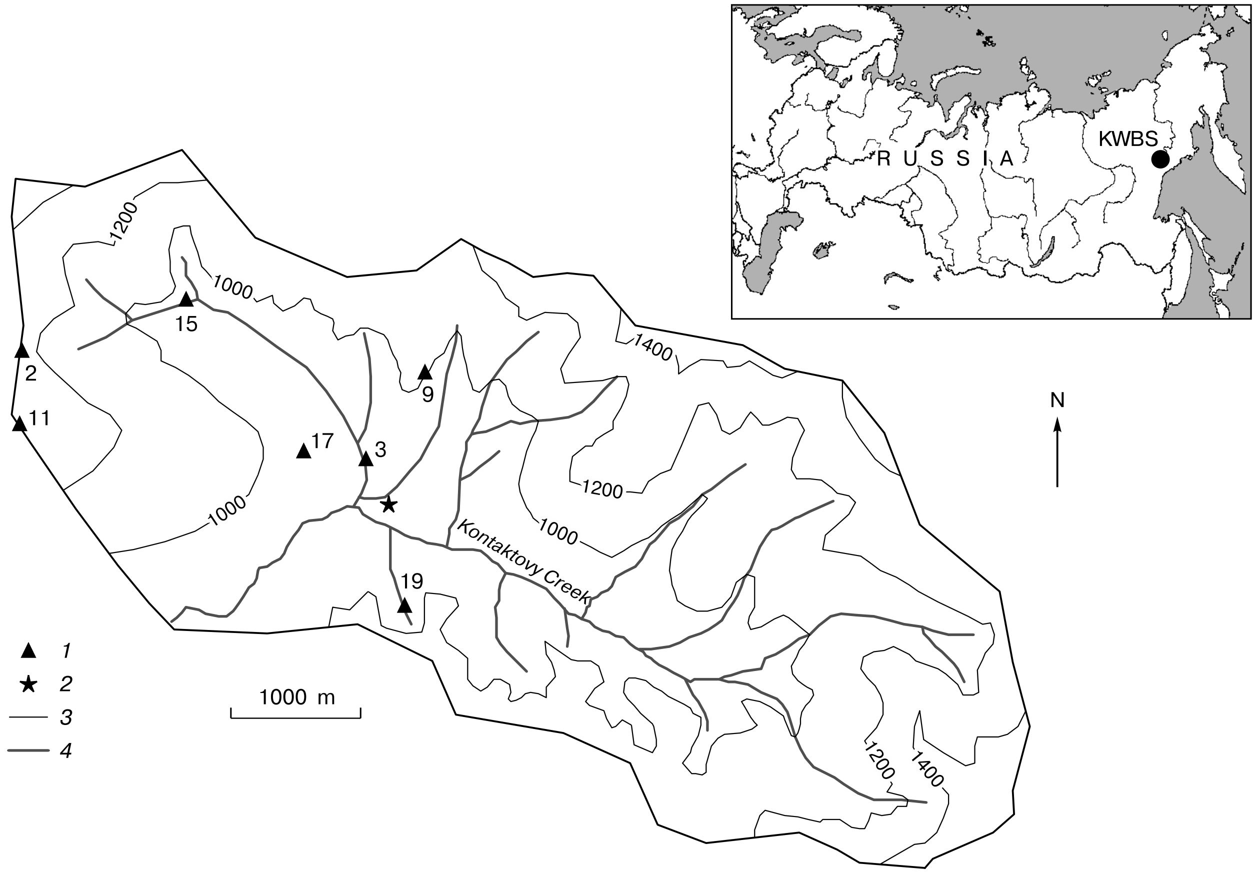

Fig. 1. Sketch map of Kolyma water balance station and its location in the map of Russia.
1 – cryopedometers; *2* – meteorological site; *3* – horizontal contour lines; *4* – creek.

when all snow has melt, the ground approaches 0 °C and remains permeable till the frost table. As the ground warms up, the pore ice melts and the meltwater rapidly flows down; some of it becomes captured at the permafrost barrier and freezes up filling all pores with ice. The thaw depth reaches 1.6–1.8 m. Almost all spring and summer rainfall flows down to the frost table through talus.

The active layer behavior in the middle parts of south-facing slopes covered with dwarf pine and typical alpine tundra vegetation is intermediate between the two.

The soil and vegetation variability, along with rugged topography, creates diverse active layer and runoff conditions. They can be efficiently simulated due to the exceptional wealth of field data collected at KWBS from 1948 through 1997.

SIMULATING SEASONAL THAW IN DIFFERENT KWBS LANDSCAPES

The active layer dynamics was simulated at seven cryopedometer sites (Fig. 1; Table 1) located in the central and western parts of KWBS at elevations from 890 to 1315 m a.s.l. The sites, with different combinations of soil, vegetation, and slope conditions, were chosen proceeding from the amount and quality of data. Evidence of the soil profiles and freezing/thawing patterns was taken from published reports [*Observation Reports, 1959–1991; Boyarintsev, 1988; Bantsekina, 2001; Glotov, 2002*], photographs, and maps.

Simulation was performed with input data of daily temperature and humidity of air and precipitation measured at the Nizhnyaya (Lower) meteorological site. The precipitation and temperature data were corrected for elevation. The variations of temperature gradient from –0.5 °C/100 m in summer to 2.2 °C/100 m in winter were approximated by monthly means measured at the Verkhnyaya (Upper) and Nizhnyaya sites at 1220 m and 850 m a.s.l., respectively. The correction coefficients to precipitation at Nizhnyaya (0.9 to 1.3) were applied separately for each cryopedometer according to the precipitation distribution at KWBS [*Lebedeva, 2012*].

Four cryopedometers were placed in talus (Nos. 9 and 11), alpine tundra (No. 2), and sparse forest

Table 1. **Location, soil type, vegetation and slope parameters at different cryopedometer sites**

No.	Location	Soil	Vegetation	α, deg	*H*, m	β, deg	γ, %
2	Saddle between two hills	Sand and clay	Mountain tundra	–	1261	0	15
3	SW-facing slope	Clay and peat	Light forest, dwarf birch, sphagnum, lichen	200	890	9	15
9	Watershed	Shale clasts	No vegetation	–	1010	0	0
11	Watershed plateau	Granite blocks and their clasts	No vegetation	90	1315	3	0
15	Steep SE-facing slope	Shale clasts with grey clay cement	Sparse light forest, moss, dwarf pine	135	952	30	15
17	River valley	Clay and peat	Light forest, moss, blueberry shrubs	0	914	5	15
19	NWW-facing slope	Clay silt and peat	Sparse light forest, lichen, blueberry shrubs	335	900	26	30

Note. α – slope direction; *H* – elevation a.s.l.; β – slope height; γ – shadow.

(No. 15); the others (No. 3, 17, 19) occurred in larch forest, with a moss-lichen floor, growing upon clay-peat soil. Average maximum thaw depths were 0.6–0.7 to 1.4–1.5 m.

For the purpose of simulations, the diverse site conditions were described by a combination of soil and vegetation properties and slope parameters that control the amount of incoming solar heat. The sites were divided into four groups: (1) talus; (2) alpine tundra and dwarf pine; (3) sparse forest with a moss-lichen layer; (4) light (larch) forest. The soil and vegetation parameters were generalized to make them applicable to active layer simulations for any site with the same sets of parameters. The four types of sites had their corresponding soil profiles.

Talus: uniform soil profile consisting of outsize shale clasts; low moisture holding capacity and high thermal conductivity, favorable for rapid and deep thawing.

Dwarf pine: soil profile same as in talus but with a moss-lichen cover; high porosity, water holding capacity, and infiltration rate of the moss-lichen layer providing insulation and reducing thaw depth.

Sparse forest: soil profile with a peat layer of high porosity and water holding capacity and low thermal conductivity, lying between 10 and 20 cm below the moss-lichen layer and over shale clasts.

Larch forest: soil profile likewise with a peat layer between 10 and 40 cm depths, lying over clay with shale clasts; low infiltration rate and thermal conductivity but high porosity and water holding capacity.

Correspondingly, the soil layers are of four types: moss-lichen layer, peat, clay with shale clasts, and shale clasts with fine-grained cement (Fig. 2).

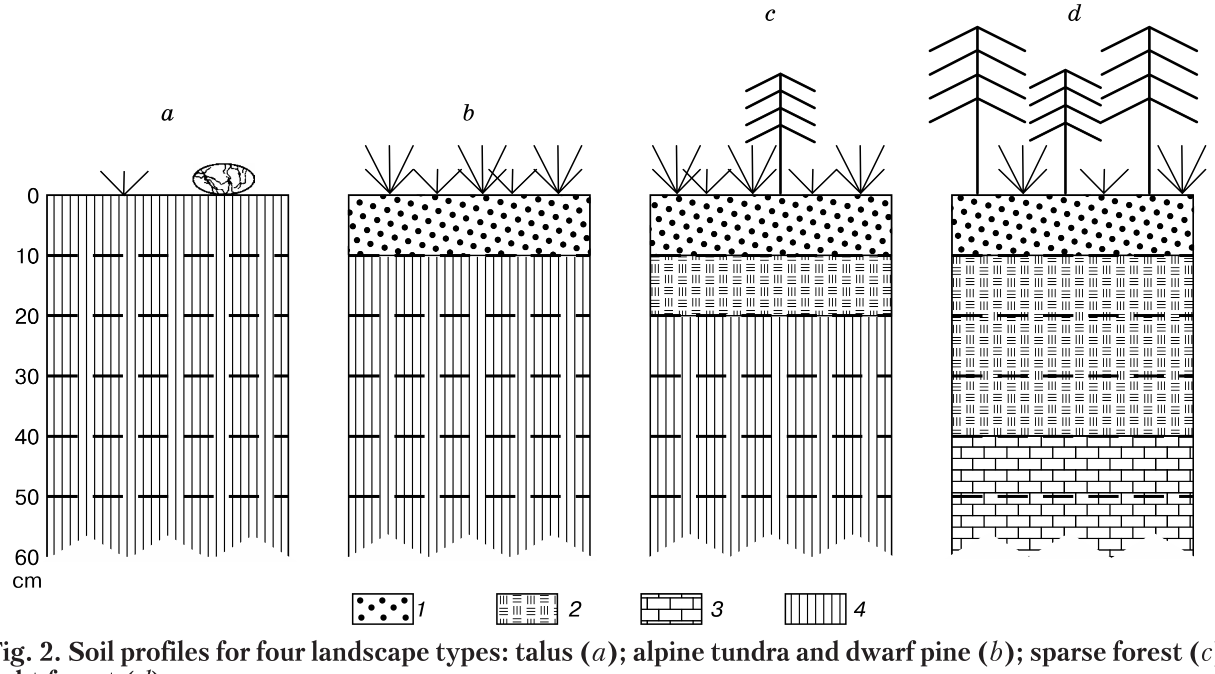

Fig. 2. Soil profiles for four landscape types: talus (*a*); alpine tundra and dwarf pine (*b*); sparse forest (*c*); light forest (*d*).

1 – moss and lichen; *2* – peat; *3* – clay with shale clasts; *4* – shale clasts.

Table 2. **Generalized properties of soil layers of four types**

Soil type	ρ, kg/m^3	ε	ω	k·10^5, m/s	c_m, J/(kg·K)	λ, W/(m·K)
Moss-lichen cover	500	0.9	0.6	17	1930	0.8
Peat	1720	0.8	0.2–0.4	0.00085–0.85*	1930	0.8
Clay with shale clasts	2610	0.55	0.13	0.000 85	840	1.2
Shale clasts	2610	0.35	0.07	0.1–1.7	750	1.5

Note. ρ – density; ε – porosity; ω – maximum water holding capacity; k – infiltration rate; c_m – specific heat; λ – thermal conductivity.

* depends on decomposition degree.

Estimating the typical soil physical properties used as input in the *Hydrograph* model (Table 2) was the principal and most difficult part of the project. The parameter values were borrowed from publications (e.g., the thermal properties of talus from [*Glotov, 2002*] and [*Bantsekina, 2003*]) and updated in the course of multiple numerical experiments. The moisture holding capacity of talus was assumed to be 7 mm, proceeding from the maximum between 2 mm and 20 mm per 1 m reported for coarse talus [*Boyarintsev, 1988*] and from the abundance of shale clasts with fine-grained cement over the KWBS area. The density and porosity of the moss-lichen and peat layers were found with reference to data of *Volokitina and Sofronova* [*2008*] for the Nizhnyaya Tunguska basin.

The 2 m thick soil profile (at the maximum thaw depth 1.7 m) was simulated as a sequence of 20 layers, 10 cm each. The ground temperature at the depth 3.2 m was used as the lower boundary condition assumed to be the climate norm, as in [*Gusev and Nasonova, 2010*]. Annual variations of soil temperature at this depth were approximated by a biharmonic function based on observations at the Nizhnyaya site [*Vinogradov et al., 2015*], with the coefficients: average –3.7 °C; first and second phases 197 and 140; first and second amplitudes 2.9 and 0.6 °C.

The heat flux from air to soil depended on the model parameters related to vegetation: canopy shadow and albedo. The variations and properties of vegetation were approximated by a phenological cycle with four key dates: start and end of growing season (points 1 and 4) and start and end of vigor growth (points 2 and 3) [*Vinogradov, 1988*].

The starting model included temperature and water (ice) content of each soil layer on the starting date of 1 January 1950, with their values corresponding to those typical of early January in the area. The initial temperature distribution was assumed to be uniform, with a mean of –1 °C for each simulation layer; the initial ice contents of soil layers were specified assuming the ice content equal to the maximum water holding capacity till the summer thaw depth (1.7 m) and to porosity below this depth, where soil is cemented with ice [*Bantsekina, 2001*].

RESULTS

Daily thaw/frost depths at the seven sites of different landscapes were estimated continuously for the period 1950 through 1990. The simulated and measured thaw depths at three typical sites of talus (cryopedometer 11), sparse forest (No. 15), and larch forest (No. 19) are plotted in Fig. 3; statistical simulated and observed thawing and freezing data from all cryopedometers are compared in Table 3.

The maximum simulated thaw depths are from 0.67 m (No. 19, light forest) to 1.57 m (No. 9, talus) and their observed counterparts are 0.60 and 1.52 m, respectively. The misfit between the simulated and observed long-term means reaches 0.13 m for No. 2 but is within 0.08 m at other points. The average absolute difference between daily depths of spring-summer thaw is from 0.08 to 0.16 m (cryopedometers 3, 15). The fall frost depth is slightly less accurate: the misfit is from 0.10 to 0.33 m.

The simulated thaw depths are shallower than the observed values (positive misfit) for both cryopedometers in talus (9, 11) but are deeper (negative misfit) for the larch forest (Nos. 3, 17, 19), alpine tundra (No. 2), and sparse forest (No. 15) sites. All simulated frost depths are generally underestimated at all cryopedometers except No. 2.

The difference between simulated and measured thaw depths for cryopedometers 11 (1964–1966) and 19 (1984–1986) shows seasonal variations (see it plotted as a function of time in Fig. 4). Namely, the simulated thaw depths at site 19 are shallower than the measured ones (positive misfit) in the thaw season but are slightly deeper (negative misfit) in the summer and fall. The difference for cryopedometer 11 (talus) is mostly positive for the whole warm season, i.e., the simulated thaw is shallower than the observed depths. The lag of the predicted thaw onset behind the observed time in both cases may result from a respective lag in the onset of snow melting, because the *Hydrograph* model lacks a unit which would explicitly account for snow redistribution. The positive to negative seasonal misfit variations result from different heat and moisture patterns in the soil profiles of permeable talus and peat-bearing soil with high water holding capacity.

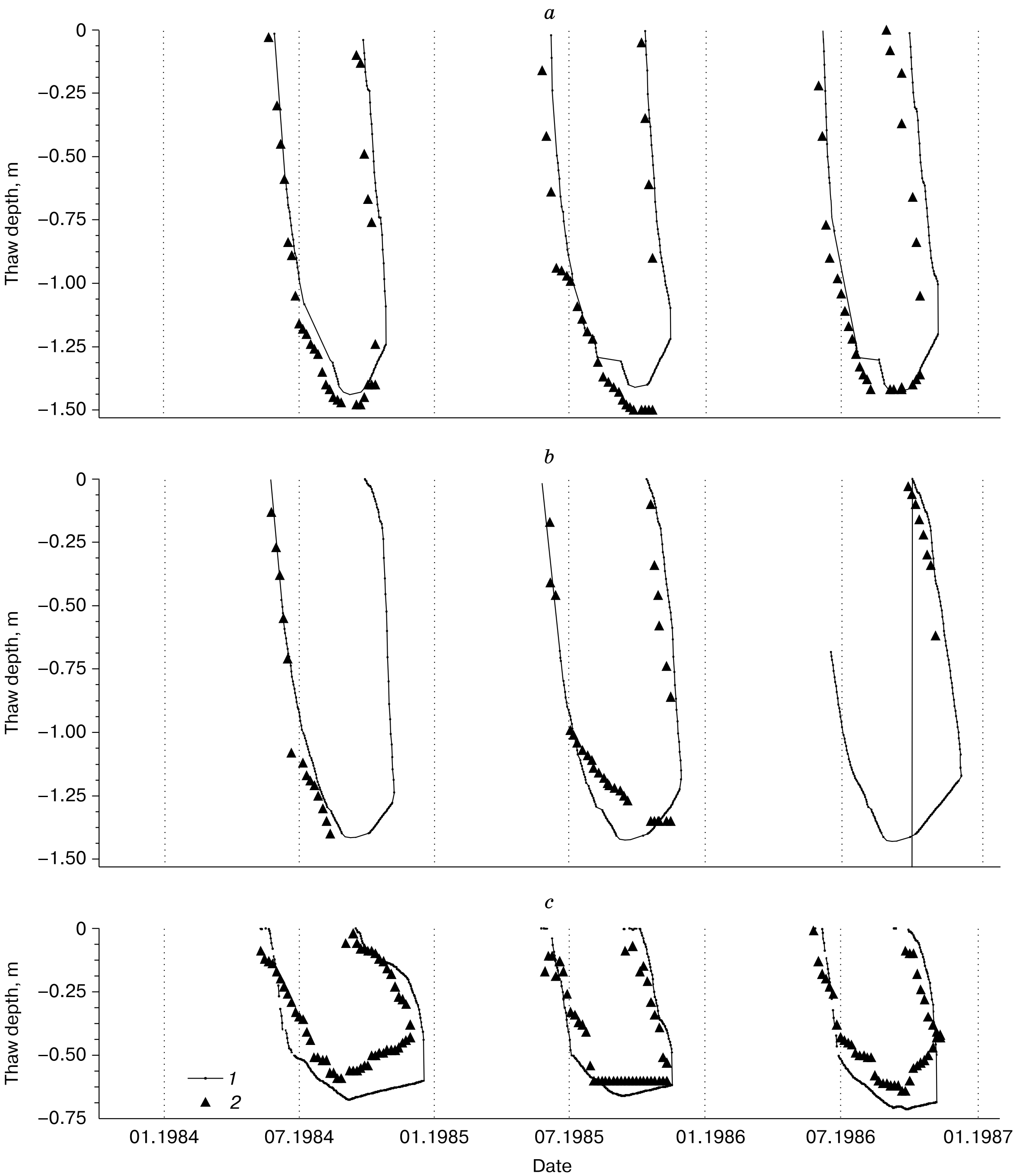

Fig. 3. Simulated and observed thaw depths at three typical cryopedometer sites:
No. 11 (talus) (*a*); No. 15 (sparse forest) (*b*); No. 19 (light forests) (*c*).

Table 3. **Simulated and observed daily thaw/frost depths, compared. Statistic results**

No.	H_{obs}	H_{sim}	Spring-summer thawing				Fall freezing				Simulation period
			Δ_{abs}	rms	N	Δ	Δ_{abs}	rms	N	Δ	
2	−1.28	−1.41	0.12	0.16	299	−0.10	0.24	0.38	92	−0.06	1954–1966
3	−0.81	−0.80	0.08	0.11	167	−0.05	0.27	0.49	64	0.05	1955–1963 (except 1958, 1959)
9	−1.52	−1.57	0.13	0.19	210	0.03	0.23	0.25	38	0.23	1960–1966
11	−1.44	−1.40	0.12	0.20	276	0.10	0.33	0.39	93	0.33	1956–1965
15	−1.36	−1.37	0.16	0.29	174	−0.07	0.31	0.44	40	0.20	1960–1966
17	−0.72	−0.73	0.12	0.16	790	−0.08	0.15	0.19	219	0.14	1964–1990 (except 1965, 1970)
19	−0.60	−0.67	0.11	0.13	408	−0.08	0.10	0.12	98	0.09	1962–1988 (except 1966–1971, 1974–1977, 1979, 1981, 1982)

Note. H_{obs} – maximum observed thaw depth, m: long-term means; H_{sim} – maximum simulated thaw depth, m: long-term means; rms – relative error, m; Δ_{abs} – average absolute error, m; Δ – average misfit (positive or negative) between simulated and observed data, m; N – length of daily values series.

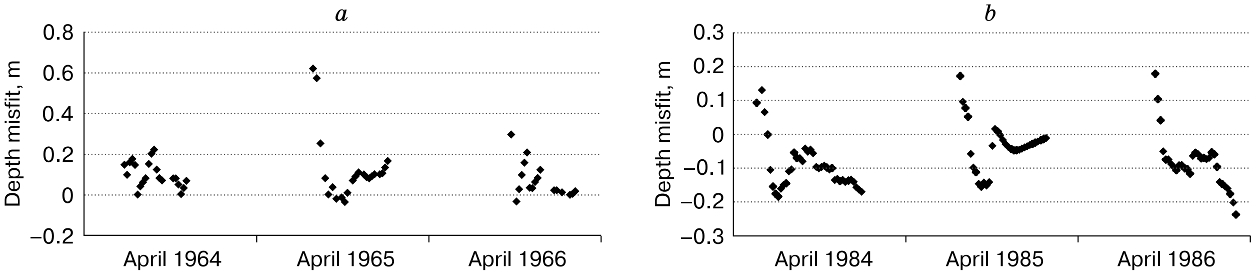

Fig. 4. Time-dependent difference between simulated and observed thaw depths at three typical cryopedometer sites:

No. 11 (talus) (*a*); No. 19 (light forests) (*b*).

CONCLUSIONS

Interactions of soil, water, and ice in permafrost are interrelated and highly variable even within a small territory of the Kolyma water balance station. Therefore, hydrological modeling has to account for the dynamics of active layer in different landscapes.

The *Hydrograph* model, used to simulate soil heat dynamics in the previous study, has demonstrated its efficiency in simulations of seasonal thaw depths at seven cryopedometer sites within KWBS located in the landscapes of rocky talus, sparse forest, alpine tundra, and light (larch) forest.

Good agreement between simulated and observed thaw depths at all sites indicates that the soil profile types and the model parameters describing their properties can be used for reference in simulations of the KWBS active layer dynamics.

The parameters of the *Hydrograph* model, which mostly refer to surface soil and vegetation, can be grouped according to landscape types and extrapolated to other objects with similar natural conditions. Therefore, the model is a reliable tool for assessment and prediction of processes in permafrost, including active layer thickness variations controlled by climate and landscape.

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