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Abstract. Detailed monitoring of soil temperature provides a unique experimental material for studying the complex processes of heat transfer from the surface layer of the atmosphere to the soil. According to air temperature monitoring data, within each of the key areas there are no significant differences between the data of the observation sites. According to annual (2011-2018) observations of soil temperature, it has been found that the microclimatic properties of bog ecosystems clearly manifest themselves in the characteristics of daily and annual variations of soil temperature. The thickness of the seasonally frozen layer at all sites is 20-60 cm, and maximum freezing of the peat layer is reached in February-March. There is evidence of degradation of the seasonally frozen layer that occurs both from above and from below. It has been found that similar bog ecosystems in different bog massifs may have significantly different temperature regimes. The peat stratum of northern bogs may be both warmer (in winter) and colder (in summer), in comparison with some bogs located 520 km to the south and 860 km to the west.

1. Introduction

An important uncertainty in predicting climate change is caused by the lack of knowledge about the state of the land surface. This issue is mainly related to the determination of energy, moisture, and greenhouse gas fluxes from the surface, temperature and humidity in the atmospheric surface layer, and the state of vegetation. In addition, high-quality maps of the distribution of ecosystems of various types are often lacking. The surface fluxes mentioned above are characterized by complex feedbacks between the atmosphere and terrestrial ecosystems. These relations have pronounced regional features in the wetlands of Western Siberia. Wetland ecosystems are included in some modern climate models as a specific type of underlying surface.

The thermal regimes of peat and mineral soil differ significantly. According to long-term (2011-2018) observations of the soil temperature regime of the oligotrophic bog “Bakcharskoye”, it was found that the microclimatic specificity of bog ecosystems is clearly manifested in daily and annual variations in the soil temperature. Peat soils are colder than mineral ones by 8-10 °C in warm time and warmer in the cold season by 1-3 ° C [1].

The peat deposit is a complex organic-mineral system with specific properties: high water content and porosity; it keeps a large amount of poorly decomposed organic matter [2]. In low humid places with a large amount of organic matter, low thermal conductivity often promotes freezing on the soil surface in spring and autumn, and thick peaty soils in the northern latitudes contribute to the elevation of permafrost and its advance to more southern areas. The thermal transport in the peat deposits of wetlands, especially during the period of freezing and thawing, depends on the processes of heat production or absorption by phase transitions of water. In other words, the heat propagation velocity in a peat deposit is determined by the effective thermal diffusivity, which is established experimentally [3]. A number of works have been devoted to model estimates of the thermophysical characteristics of soil in the tundra zone based on temperature profile measurements.

Studying the temperature regime of peat soils is an important task, since the highest rates of modern warming are in the northern latitudes [4], where the main reserves of peat (and carbon) are located. According to various estimates, peatland ecosystems contain about 120–455 billion tons of carbon [5],[6]. In Russia, carbon stocks in the form of peat are estimated as 215 billion tons [7]. Peatlands of Western Siberia contain up to 70 billion tons of carbon [8]. Such a significant amount of carbon as a result of climate change or anthropogenic impact can potentially partially go into the atmosphere in the form of CO_2 or CH_4 and make a significant contribution to the carbon balance of the atmosphere [9].

It should also be emphasized that detailed monitoring of the temperature of the soil layer provides a unique experimental material for studying the complex processes of heat transfer from the surface layer of the atmosphere to the soil.

In the state-of-the-art models of the active land layer, such as the CLM [10] and JSBACH [11], the thermodynamic regime and moisture transfer in wetlands are reproduced taking into account the porosity and thermal conductivity characteristic of the peat soil types. Both models use the TOPMODEL, which calculates the level of groundwater taking into account the subgrid scale orography, surface runoff, and precipitation.

In these land surface schemes, only one type of wetland soil with the properties averaged over a variety of wetlands is taken into account, while, for example, the CLASS model [12] accounts for the difference between different types of wetlands, in particular, in moisture diffusivity. Also, different types of wetlands have different thermodynamic regimes and physical properties, both during autumn freezing and spring melting.

In the model of the active soil layer of INM RAS (Institute of Numerical Mathematics, Russian Academy of Sciences) and Moscow State University, the land is divided into 5 types of surface: vegetation, open soil, water bodies, snow, and a layer of intercepted moisture (raindrops remaining on the leaves, surface moisture film on the soil, etc.). Land cells contain different fractions of these types, which depend on time. The differences in surface types are taken into account in the surface heat balance equation through the following characteristics: roughness lengths, air humidity at the surface, surface stomatal resistance, geographical differences in the model for land cells, the fractions of sand and clay in soil, depth of lakes. The distribution of surface types, the ocean surface temperature is represented for each of the 12 months, and the albedo of the land surface which is free from snow - for January, April, July, and October. The state of the active layer in the INM RAS-MSU model is characterized by ten values. As initial conditions of the variables, value fields are used, which are external parameters of the active layer model.

In the soil, solid particles of three fractions are considered: sand, silt, and clay. The data obtained characterize the texture of the soil stratum as a whole. However, it is assumed that the clay fraction corresponds to the organic matter of the soil and is concentrated in the upper layers of the model to a level of 70 cm [13].

In the model, there is no such soil type as peat or another type close to it in the hydrodynamic properties. Within the framework of this work, it is necessary to understand whether it is possible, with the land surface model formulation and the physical parameterizations, to reproduce the temperature and moisture conditions, in both mineral and peat soils, differing only the external soil parameters that are responsible for its hydrodynamic properties.

By peat soils we mean soils of oligotrophic bogs in which the groundwater level depends more directly on precipitation falling on the bog ecosystem itself, and not on the surface runoff from the territories surrounding the bog, as in the case of eutrophic bogs [3]. That is, remaining within the framework of the equations of heat and moisture transfer of the soil, we can estimate the correctness of the reproduction of the groundwater level in oligotrophic bogs depending on precipitation and mechanical properties of the soil.

2. Measurement data

Field studies of the soil temperature regime were carried out in the eastern part of the Ob-Irtysh interfluve, within the eastern margin of the Vasyugan Plateau in 2011-2018 [14]. The mean annual air temperature for 1936–2017 is –0.3 °C, with July ranking warmest (18.1 °C), and January (–19.2 °C) coldest on the records. The total annual precipitation amounted to 468 mm, of which 45 % fell in the summer months and 12 % during winter [15].

Observation sites were organized at two contrast soil types. The first site was located within the territory of the Bakchar weather station with clay loam soil [15]. The Bakchar weather station is situated on the Bakchar river terrace, where the soil is described as sod-gley heavy-textured clay loam. The surface vegetation cover is short grass mowed several times in summer.

The second site was at a typical oligotrophic treed bog with peat soil [16]. Oligotrophic peatlands with a narrow set of forming species occupy a dominant position in the study area. The treed pine-shrub-sphagnum bogs (ryams) is the most widespread type of bogs in the south taiga subzone. The low ryam microorography is wavy due to a large number of large moss hummocks about 30 cm high and up to 3 m in diameter. The peat thickness at the observation site is 2.1 m.

The measurements of the soil temperature were performed at several depths from the surface to 240 cm (0, 2, 5, 10, 15, 20, 30, 40, 60, 80, 120, 160, 240 cm), and the air temperature was measured at a height of 2 m using an atmospheric-soil measuring complex [17]. The depth-time distribution of the soil temperature for the two studied sites is shown in Figure 1.

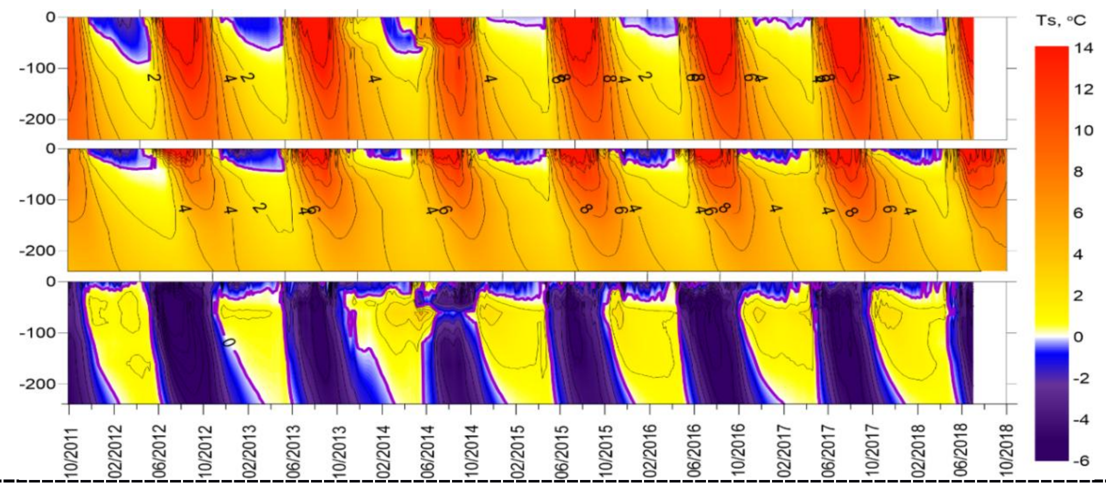

Figure 1. Soil temperature for clay loam soil (top), peat soil (middle), and soil temperature difference (bottom) (Tpeat – Tclay).

The maximum of long-term average surface temperature at the weather station was observed in July (20.3 ^{o}C), and the minimum in February (-0.9 ^{o}C) beneath a thick snow cover. The surface temperature at the bog is lower than at the weather station reaching 17.8 ^{o}C in July and – 2.4 ^{o}C in January. The difference in the soil temperatures between the sites is negligible in winter with – 0.6 ^{o}C at a 20-cm depth in February at both sites, and it raises in summer with 18.4 ^{o}C and 13,8 ^{o}C at the clay and peat soils, and subsequently in July at 20 cm. The maximal positive temperature difference between the sites is observed in July at a depth of 60 cm with the soil temperatures reaching 15.3 ^{o}C and 10,6 ^{o}C at the clay and peat soils, subsequently. The most pronounced negative temperature difference (– 2.1 ^{o}C) was registered in November at a depth of 60 cm with clay and peat soil temperatures of 2.7 ^{o}C and 4.8 ^{o}C. At a depth of 240 cm, the annual temperature variations in the clay soil are in the range from 2.9 ^{o}C (April) to 9.5 ^{o}C September), while in the peat soil the temperature varies from 3.3 ^{o}C (June) to 5.0 ^{o}C (November).

The top 20-cm layer of peat soil is always colder than in clay soil, but deeper peat soil layers are warmer in winter and colder in summer. The observed temperature differences are related to essentially different soil composition and extremely high soil moisture of the peat soil.

3. Modeling results

The modified INM RAS-MSU land surface scheme (LSM) was used to simulate the temperature regime of mineral and peat soils. This version of the model is a software package decoupled from the Earth System model and capable of working both in single-column mode for a specific point of interest regional and global modes, the latter simulating the whole land surface of the Earth. Atmospheric forcing can be taken from both measured data sets and simulation results, produced by climate models or reanalyses. This allows to configure the model for a specific study area and verify the result using local measurement data.

We used the single-column mode of INM RAS-MSU LSM to perform numerical experiments. As atmospheric boundary conditions, we used the observation data on the basic meteorological variables (air temperature, humidity, precipitation between the observation periods, surface wind speed and atmospheric pressure) with increments of 3 hours, as well as the intensity of the incoming short-wave and long-wave radiation. Measurements of the above data were carried out near the installation points of soil stations.

External input parameters for INM RAS-MSU LSM related to the thermohydrodynamic properties of soils were set from experimental data obtained for the two studied sites, with clay and peat soils (Table 1), namely: b – Clapp-Hornberger dimensionless parameter; $\Psi_{\max}$ - moisture potential at saturation, m; Π – porosity; γ_{max} - maximum hydraulic conductivity, m/s; λ_{max} - maximum values of the moisture diffusion coefficient, m^2/s ; W_0 - the amount of water remaining unfrozen at 0 ºC, kg/kg; W_m - the amount of water remaining unfrozen at very low temperature, kg/kg.

Table 1. Parameters of two types of soil, clay and peat.

Physical parameter	Clay	Peat
b	5.30	11.40
$\boldsymbol{\Psi_{\max} * 100}$	56.6	18.6
Π	0.31	0.850
$\boldsymbol{\gamma_{max} * 100}$	0.00072	0.0001
$\boldsymbol{\lambda_{max} * 10000}$	0.20400	0.00926
$\boldsymbol{W_0}$	0.18	0.40
$\boldsymbol{W_m}$	0.07	0.20

During the numerical experiments, in contrast to the basic version of the LSM_INMCM, one hundred percent content of the same type with properties from Table 1 that did not change depth was set at each of the calculated depth levels. Also, peat density values were introduced for peat, which were the same for all types in the basic version (Table 2).

Table 2. Density parameters of dry skeleton and saturated for clay and peat.

	Clay	Peat
ρ (dry soil), kg/m^3	1200	100
ρ (solids), kg/m^3	2650	1550

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Of course, in reality the property of the soil, in particular, the porosity of peat, varies greatly with depth and it is necessary to set the hydrodynamic properties of the soil as a function of depth, but for this model it cannot be done.

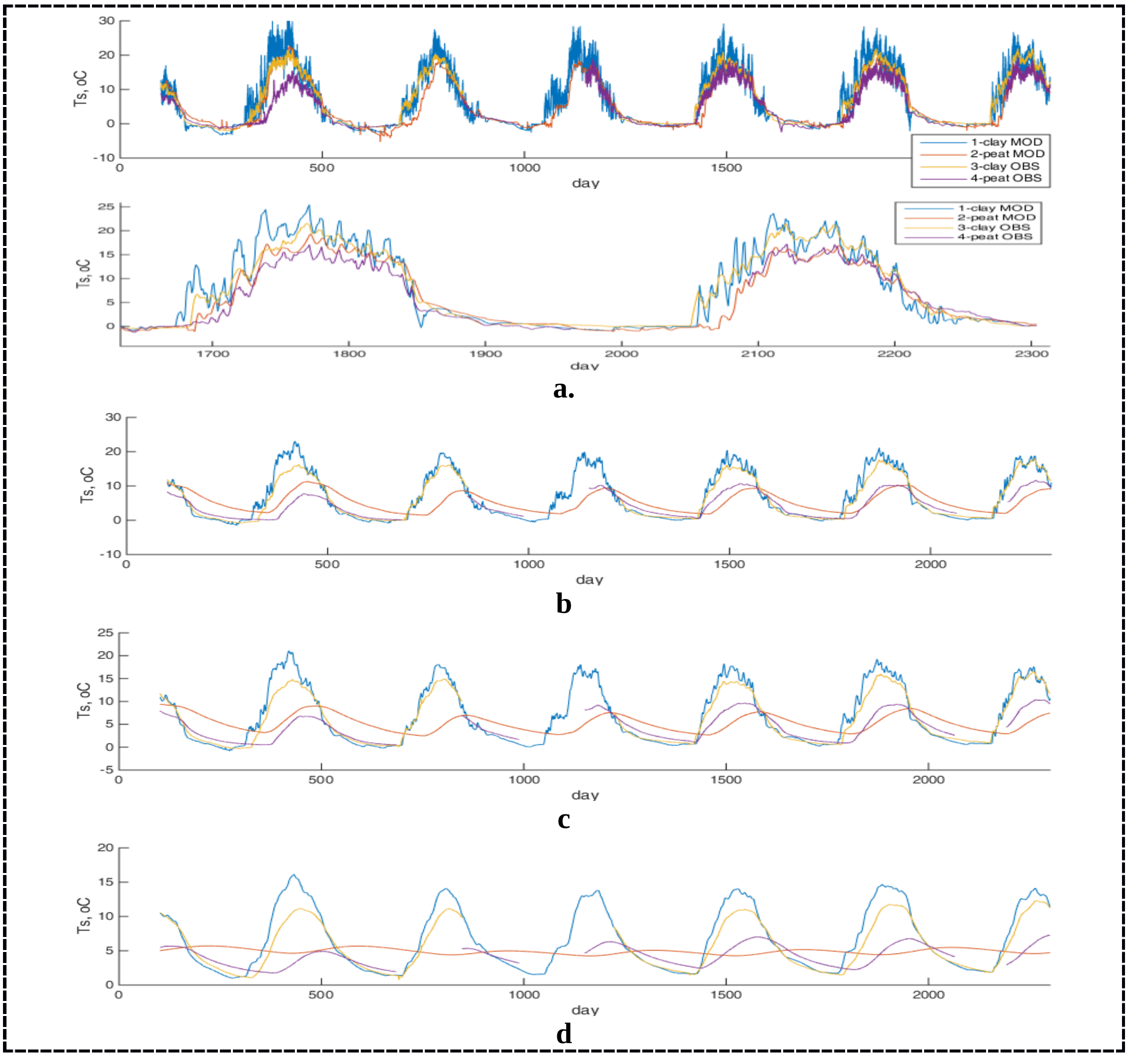
In order to simulate heat and moisture transfer in soil, in addition to boundary conditions, initial conditions are also necessary. The initial distribution of the moisture and thermal characteristics of the soil can have a decisive influence on the reproduction of the thermal regime of the soil cover. Therefore, at the initial time it is necessary to know with sufficient accuracy the depth distribution of the soil temperature, as well as the amount of liquid and frozen moisture in fractions of dry soil. The initial temperature and humidity profile can be determined from the measurement data, and the ice content in the pore space of the soil in July can be set to zero.

The calculation period was 8 years, 2011-2018, identical to the measurement period.

4. Results

As seen in Figure 2 and Figure 3, in the case of clay soil the temperature has a similar amplitude and close values, both on the surface and to a depth of 160, and for the deeper layer the correlation coefficient between the modelled and observed data decreases.

In peat soils we see a clear shift in the amplitude with increasing depth (Figure 2) and an increase in the absolute error (Figure 3), while on the surface, up to 40 cm, the temperature is reproduced quite correctly.



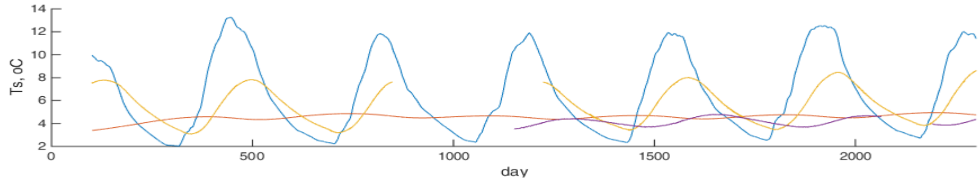


Figure 2. Daily average temperature modelled and observed data for 2011 to 2018: a. 20 cm; b. 60 cm.; c 80 cm.: 160 cm.: 320 cm depth.

The surface temperature in the active layer is completely determined by the atmospheric exposure and radiation forcing. In deep soil there are discrepancies associated with improperly described hydrodynamic properties which vary quite a lot with depth. The not enough correct reproduction of the groundwater level affects inertia in the processes of thawing and freezing as well.

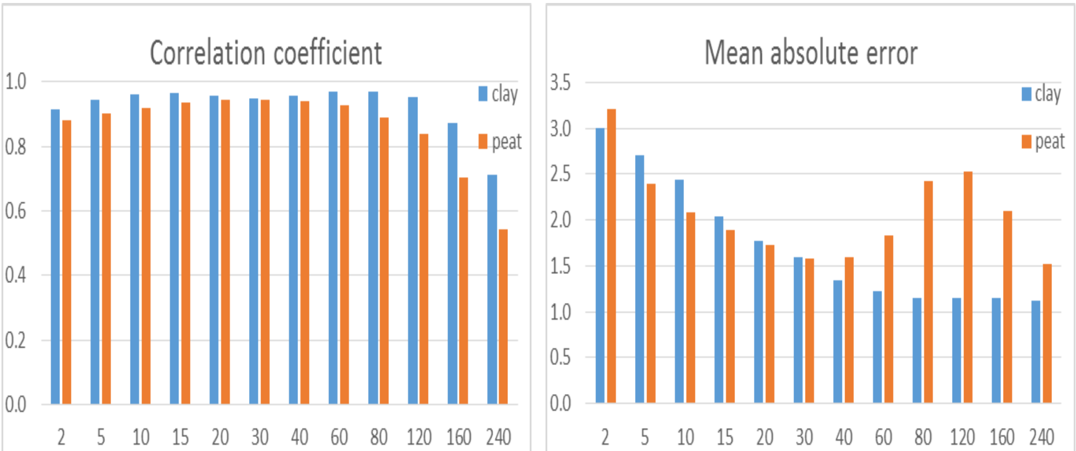


Figure 3. Correlation coefficient and mean absolute error for modelled and observed data. Average for 2012 to 2018.

In cases of moisture on the surface (Figures 4 and 5), both clay and peat reproduce seasonal freezing quite correctly. For clay this is about 90 cm, and for peat 30 cm. With depth, both types are represented as saturated with water, which is a characteristic for the West Siberian lowland. In the case of peat, the surface processes have no influence on humidity below 150 cm for all months, which is correctly reproduced (all lines collapse (Figure 5)). This, of course, in reality is connected with the presence of groundwater. Moreover, for peat the volume of moisture below 150 cm is reproduced as being of significantly lesser value, 0.5 m^3/ m^3, than in reality, 0.8-0.9 m^3/m^3. This is due to the fact that the ground water flow is at the lower boundary in the model, which is not correct for this type of soil in which there is hydraulic resistance in the form of a clay soil layer under a peat deposit at a depth of 1.5 -3 meters.

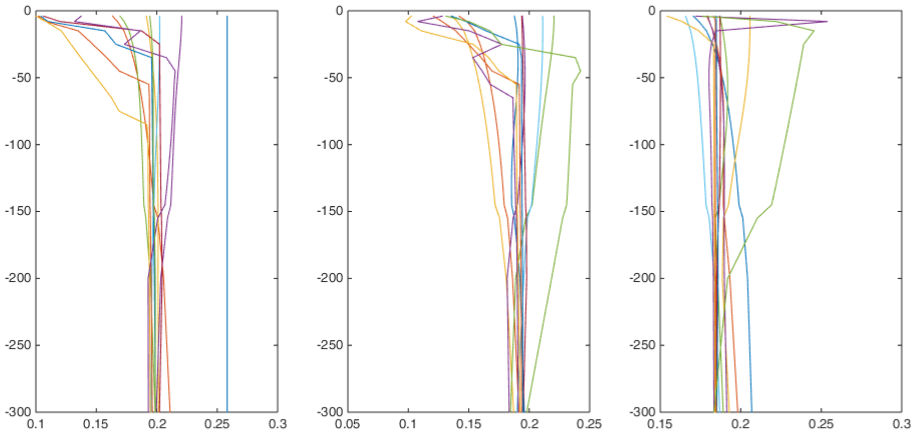


Figure 4. Monthly-averaged soil moisture profile for clay, three different years (2012, 2013, 2014).

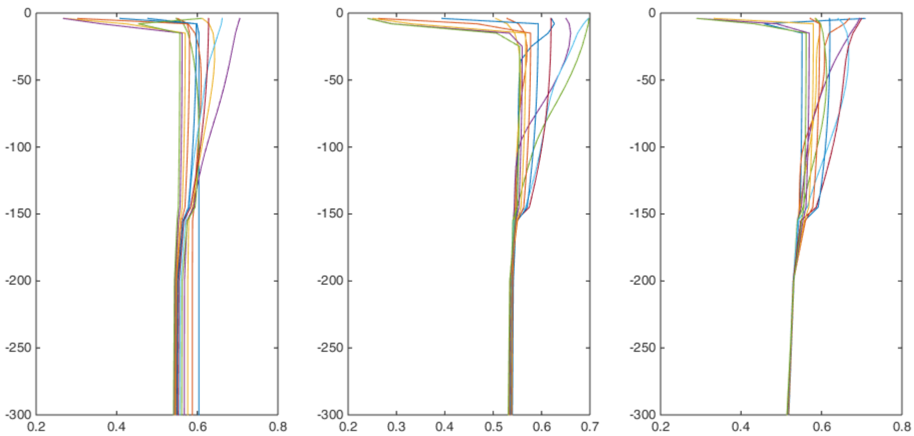


Figure 5. Monthly-averaged soil moisture profile for peat, three different years (2012, 2013, 2014).

The above analysis of the results suggests that to reproduce the temperature regime of bog ecosystems it is not enough just to introduce a new type of hydrodynamic properties, it is necessary to switch to the hydrodynamic properties of a soil as a function of depth for the correct reproduction of bogs at any depth of a peat deposit. Moreover, the above-obtained results allow us to state that in oligotrophic bogs the groundwater level can be reproduced correctly without adding any of the parameters related to the runoff.

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