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SIMULATION OF THERMAL AND MOISTURE-CONTENT CONDITIONS ON THE UPPER LAYER OF PEAT SOILS

G. P. Brovka, I. V. Dedyulya, and V. A. Sychevskii

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The problem of two-dimensional interrelated heat- and moisture-transfer in the upper layer of soil is formulated taking into account exchange by heat and moisture with the ground-level air layer. On its basis a difference scheme was constructed and algorithms and a program were developed to calculate the processes of heat and moisture transfer. We evaluated the effect of various meteorological and hydrological factors and the composition of organogenic rocks on the change in the temperature and moisture-content conditions of peat deposits and soils.

It is known that reclaimed peat soils are environmentally unstable as regards their temperature and moisture-content conditions. They are more easily subjected to droughts and frosts than mineral soils. Prediction of extremum phenomena on reclaimed soils requires scientifically justified methods for predicting the temperature and moisture-content conditions in their upper layers.

For this purpose we formulated a problem of two-dimensional interrelated heat- and moisture-transfer in the top layer of soil, taking into account the exchange of heat and moisture with the ground-level air layer. It is assumed here that heat in the soil is transferred mainly by conduction and moisture is transported by moisture conduction under the action of the overall chemical potential μ_{mat}, which depends on the moisture content u and gravity potential gh, where g is the free-fall acceleration and h is the height relative to the standard level. It is also assumed that along with the flow of liquid in the soil there is also a vapor flow induced by the partial vapor pressure P_v. The pressure P_v in the soil is a function of the temperature and the moisture content. Its specific form is determined by the dependence of the saturated-vapor pressure on temperature and by the isotherms of sorption–desorption of moisture by the soil.

The boundary conditions on the soil surface were assigned on the basis of data on radiative and convective heat exchange, and also on the convective exchange of vapor of the ground-level air layer with the soil surface. At the lower boundary of the active layer the level of groundwater H was prescribed.

Mathematically the problem is formulated in the following way:

$$\frac{\partial T}{\partial \tau} C_{ef}\rho = \frac{\partial}{\partial x}\left[\lambda(u, T)\frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda(u, T)\frac{\partial T}{\partial y}\right], \tag{1}$$

$$\frac{\partial u}{\partial \tau}\rho_{sk} = \frac{\partial q_{wx}}{\partial x} + \frac{\partial q_{wy}}{\partial y}, \tag{2}$$

$$q_{wx} = -a_w(u)\rho_{sk}\frac{\partial u}{\partial x} - \lambda_v f_{2u}'(u, T)\frac{\partial u}{\partial x} - \lambda_v f_{2T}'(u, T)\frac{\partial T}{\partial x}, \tag{3}$$

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$$q_{wy} = - a_w (u) \rho_{sk} \left(\frac{\partial u}{\partial y} - \frac{g}{f'_{1u}} \right) - \lambda_v f'_{2u} (u, T) \frac{\partial u}{\partial y} - \lambda_v f'_{2T} (u, T) \frac{\partial T}{\partial y}, \quad (4)$$

$$q_R + q_c + q_\varphi + q_{Ty} = 0 \quad \text{for} \quad y = 0 ; \quad (5)$$

$$T = T_H , \quad \mu_{mat} = 0 \quad \text{for} \quad y = H ; \quad (6)$$

$$\mu_{mat} = f_1 (u) ; \quad P_v = f_2 (u, T) . \quad (7)$$

Based on the system of equations (1)-(7), algorithms and a program were developed for a computer to calculate the processes of heat and moisture transfer in the top layer of soils-grounds with allowance for local meteorological conditions. The program was tested on a series of problems whose solution could be obtained by the methods developed earlier. The testing demonstrated the stability and convergence of the computational scheme. Comparison of test calculations of a temperature field with standard methods points to a satisfactory accuracy of the method presented.

This method makes it possible to calculate the temperature, moisture content, and moisture and heat fluxes in the top layer of soils-grounds depending on meteorological and hydrological conditions. It should be noted that in solving this kind of problem very important is the information provision of mathematical models. Therefore, carrying out experimental investigations at the Laboratory of Physicochemical Engineering of Natural Disperse Systems at the Institute of Problems of Utilization of Natural Resources and the Environment, we obtained empirical dependences of all the necessary parameters and characteristics for peat soils [1]:

$$\mu_{mat} = 10 \left(- \frac{a_1^3}{(u - a_2)^3} + a_3 \right),$$

$$P_v = P_{v0} \exp \left(\frac{L_{ev}}{R (T_0 + 273)} \frac{T - T_0}{T + 273} - \frac{\mu_{mat}}{R (T + 273)} \right).$$

For lowland sedge peat, the values of the constant coefficients are $a_1 = 1.7$, $a_2 = 0.2$, and $a_3 = 2.05 \cdot 10^{-3}$.

Heat and moisture fluxes at the interface between the soil surface and ground-level air layer were prescribed by the equations

$$q_c = - \alpha_c (T_{ss} - T_a) , \quad q_\varphi = - \alpha_c (e_{ss} - e_a) L_{ev} / c_p , \quad q_w = - \alpha_c (e_{ss} - e_{ev}) / c_p .$$

The coefficient of convective heat exchange α_c is calculated as a function of the wind velocity V and time of day from the formulas $\alpha_c = 4.0 + 2.0V$ (at night) and $\alpha_c = 8.5 + 2.0V$ (in the daytime). The character of these dependences is known from the literature [2]. But the numerical coefficients were obtained on the basis of the results of experimental investigations of heat transfer in the top layers of soil, and also of radiative and convective heat and mass exchange of ground-level air layers with the soil surface. For this purpose, two experimental plots were used with a plowing layer of peat; one on the territory of the Institute of Problems of Utilization of Natural Resources and the Environment, National Academy of Sciences of Belarus in Minsk, and the other in the Ushachi District of the Vitebsk Region 20 km from the meteorological station of the Berezina nature reserve. The third plot was laid on dried peatland on the dale of the Ushachka River 4 km from the second plot. The results of observations obtained here in 1996-1998 were used to verify the adequacy of the mathematical simulation.

To calculate the radiation balance, use is made of a procedure that is known from the literature [3]:

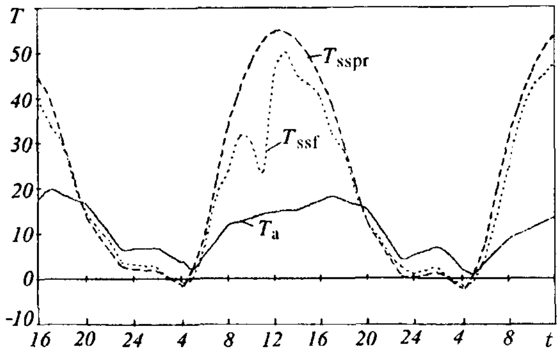

Fig. 1. Comparison of calculated and field data of the diurnal behavior of temperature on the peat-soil surface: T_a, temperature of air at a height of 2 m; T_{sspr}, soil-surface temperature (predicted data); T_{ssf}, same (field data). T, °C; t, h.

$$q_R = (1 - r) I + d (B_A - B_0) , \quad I = I^* (0.944 - 0.063\tau_f) \sin h_c ,$$

$$\sin h_c = \sin \psi \sin S + \cos \psi \cos S \cos \frac{2\pi}{\Pi} t_m ,$$

$$S = 23.5 \sin \left[(D - 81.5) \frac{\pi}{2} \frac{1}{91.5} \right] ,$$

$$B_0 = \sigma T_{ss}^4 ,$$

$$B_A = \sigma T_a^4 (0.526 + 0.065 \sqrt{P_2}) .$$

Allowance for the influence of the cloud cover on the radiation balance is made using the coefficients of the cloud amount; for shortwave radiation K_{sh} and longwave radiation K_{lg}

$$q_R = K_s (1 - r) I + K_{lg} (B_A - B_0) .$$

According to literature data [3], a change in the intensity of shortwave radiation occurs due to the coefficient K_s, which varies from 1 (no clouds) to 0.5 (with cloud amount equal to 10). A change in the intensity of longwave radiation due to the presence of clouds corresponds to the variation of K_{lg} within the limits 1–0.15.

As the input parameters that correspond to certain climatic hydrologic factors and properties of soil, we prescribed the following: the diurnal behavior of the temperature and air humidity at a height of 2 m, wind velocity (from 0 to 6 m/sec), cloud amount, day of the year, level of groundwater (from 0.5 to 2 m), temperature on the bottom of the active layer, degree of mineralization of peat soil (from 0 to 0.3), and albedo of the soil surface (from 0.03 to 0.3). The calculated parameters were the diurnal behavior of the temperature and moisture content on the soil surface, the temperature and moisture-content distributions in the top layer of the soil, and the daily balance of heat and moisture due to convective exchange of soil with the ground-level air layer.

In the main version of the calculation it is assumed that weather is without clouds, the wind speed is $V = 0$, the level of groundwater is 1 m, the fraction of the sand component in the soil is equal to zero, and the surface albedo is $r = 0.03$. In addition to the main version we carried out a series of calculations in which one of the indicated parameters was changed and also the diurnal behavior of the temperature at a height of 2 m was shifted by ±3°C.

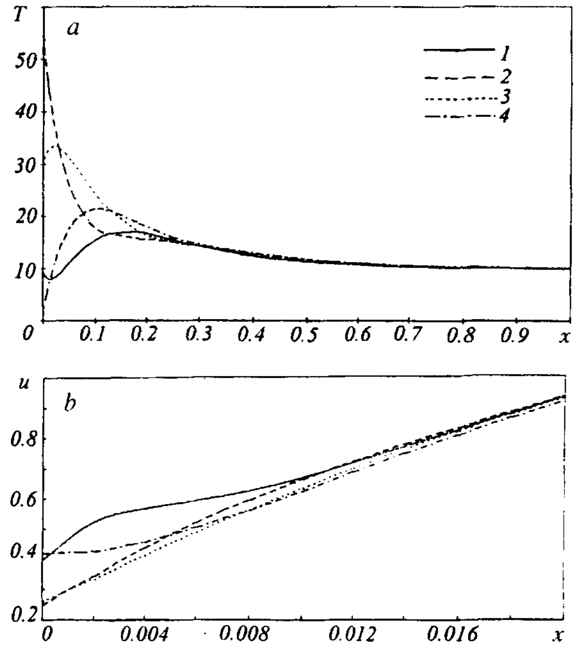

Fig. 2. Dynamics of the temperature (a) and moisture-content (b) conditions in peat soil: 1) t = 6 h; 2) 12; 3) 18; 4) 24. u, kg/kg; x, m.

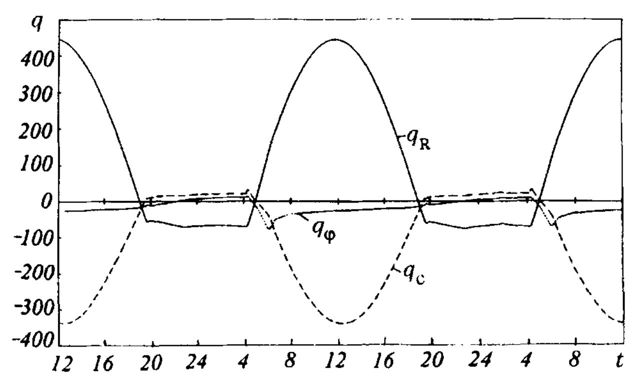

Fig. 3. Diurnal behavior of the heat fluxes on the peat-soil surface.

The results of computer simulation are presented in Figs. 1-4. Figure 1 presents the calculations of the diurnal behavior of temperature on the surface of peat soil in comparison with similar data of natural observations on the second experimental plot. As is seen from the figure, the calculated and experimental data are in satisfactory agreement. Figure 2 presents calculated curves that reflect the dynamics of the temperature and moisture-content fields in the upper layer of peat soil. According to the data presented, the amplitude of temperature fluctuations exceeds 50°C on the soil surface and –5°C at a depth of 10 cm, whereas at a depth of 25 cm the diurnal temperature fluctuations damp. The moisture content of the surface layer of peat soil changes from 0.25 to 0.5 kg/kg over 24 h. However, its fluctuations in the surface layer do not propagate deeper than 2 cm.

The calculated data on the diurnal behavior of the radiative and convective heat fluxes and of the heat flux due to evaporation or condensation of moisture on the peat-soil surface are presented in Fig. 3. As is seen from the data given, the overall radiation flux has the maximum value at midday and attains 430 W/m^2. At the same time, the convective flux also has a maximum value, but it is oppositely directed. At night the radiative and convective fluxes change their direction and decrease in absolute value. Here they are characterized by relative constancy during the night. The overall radiative heat flux at night is equal to about 100 W/m^2,

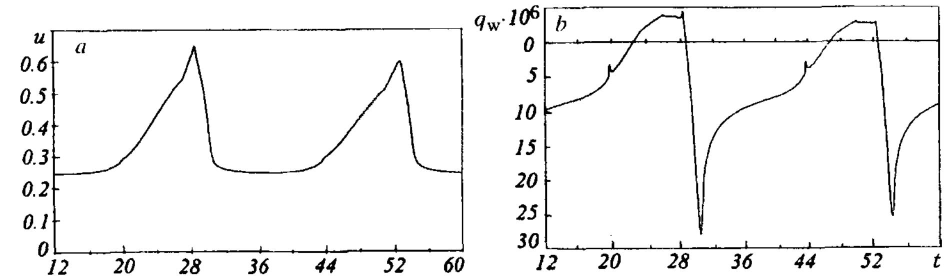

Fig. 4. Diurnal behavior of the moisture content on the peat-soil surface (a) and of the moisture flux into it (b). u, kg/kg; t, h; q_w, kg/(m^2·sec).

whereas the convective one does not exceed 20 W/m^2. The diurnal behavior of the heat flux due to the processes of evaporation and condensation of moisture is of a more complex character. This flux has a sharp peak at 8 in the morning; then its absolute value decreases throughout the day and the first half of the night. During this time the moisture evaporates from the soil. During the second half of the night, up to sunrise, the moisture undergoes condensation on the soil surface, and the corresponding heat flux has a positive value.

Figure 4 presents data on the computer simulation of the diurnal behavior of the moisture content and the moisture flux on the soil surface. From Fig. 4a it is seen that the moisture content on the soil surface increases after sunset and in about 4 h takes on the maximum value. Then in the morning it falls sharply and afterwards remains constant. This is explained by the increase in the relative humidity of air at night and decrease in temperature, which causes the condensation of moisture on the soil surface. As a result, the moisture flux into the peat soil changes its sign (Fig. 4b). In the morning, with sunrise intense evaporation begins. Thereafter, the moisture flux from the peat-soil surface decreases with simultaneous decrease in its supply from the depth to the surface. As a result, the moisture content remains nearly constant during the greater part of the day.

We carried out numerical calculations of the diurnal behavior of the temperature, moisture content, heat flux, and moisture flux on the soil surface, with the level of groundwater H, mass fraction of the sand component, surface albedo r, wind velocity V, cloud amount, and air temperature at a height of 2 m being variable.

The analysis of the calculation results showed that the increase in the level of groundwater from 1 to 0.5 m increases the minimum temperature on the peat-soil surface by 0.7°C and decreases the maximum temperature by 1.1°C. A fall in the level of groundwater to 2 m decreases the minimum temperature of the soil surface by 0.25°C and respectively increases the maximum temperature by 0.75°C. An increase in the mass fraction of the sand component from 0 to 0.3 leads to a rise of 1.3–1.5°C in the minimum temperature of the soil surface and a decline of 3°C in the maximum temperature of the soil. The increase in the soil-surface albedo basically influences the maximum temperature, decreasing it by 12°C as the albedo increases to 0.3. Here, the minimum temperature can also become lower due to the decrease in heat supply in the daytime. A wind velocity of 3 m/sec increases the minimum temperature of the soil surface by 1.5°C and decreases the maximum temperature by 10°C. As the wind velocity increases up to 6 m/sec, the rate of change in the temperature somewhat decreases. The cloud amount exerts the most substantial effect on the soil-surface temperature at night. Thus, with a cloud amount of 10 the minimum temperature of the soil surface may increase by 5°C. A change in the air temperature at a height of 2 m leads to an equivalent change in the soil-surface temperature both at night and in the daytime.

The influence of the indicated factors on the heat flux on the soil surface is mainly similar to their effect on the surface temperature, except for the air-temperature variation, which virtually does not change the magnitude of the heat flux.

The analysis of the obtained results on the influence of meteorological and hydrological factors and the component composition of soils on their moisture-content conditions shows that the minimum moisture content virtually does not change. However, the maximum moisture content is higher in those versions where the temperature of the soil at night is respectively lower. This behavior is especially distinct in the version where the cloud amount varies. This trend can be explained by the moisture condensation on the soil surface at night. This assumption is also confirmed by the data on the comparison of moisture fluxes on the surface of soils with variation of the factors considered.

Thus, using the method of computer simulation, it is possible to evaluate the effect of various meteorological and hydrological factors, as well as that of the composition of organogenic rocks, on the change in the temperature and moisture-content conditions of peat deposits and soils, which makes it possible to predict extremum climatic phenomena on reclaimed soils and to decrease economic losses incurred by them.

NOTATION

T, temperature, $^{\circ}$C; $C_{eff}(u, T)$, effective specific heat capacity of the soil, J/(kg·K); ρ, soil density, kg/m^3; $\lambda(u, T)$, thermal conductivity coefficient of the soil, W/(m·K); u, moisture content, kg/kg; τ, time, sec; ρ_{sk}, density of the soil skeleton, kg/m^3; a_w, coefficient of moisture diffusion, m^2/sec; λ_v, coefficient of vapor permeability, sec; μ_{mat}, matrix potential of moisture, J/kg; $f_1(u)$ and $f_2(u, T)$, functions showing the dependence of the matrix potential and vapor pressure on the moisture content and temperature; f'_{1u}, f'_{2u} and f'_{2T} – $\partial f_1/\partial u$, $\partial f_2/\partial u$, and $\partial f_2/\partial T$, respectively; q, heat flux; W/m^2; q_R, overall radiative flux, W/m^2; q_c, convective heat flux, W/m^2; q_{φ}, heat flux due to moisture evaporation and condensation, W/m^2; q_{Ty}, conductive heat flux on the soil surface, W/m^2; q_w, moisture flux, kg/(m^2·sec); c_p, air heat capacity at constant pressure, J/(kg·K); P_v, partial vapor pressure, Pa; P_{v0}, partial vapor pressure at $T_0 = 0^{\circ}$C, Pa; R, universal gas constant, J/(mole·K); L_{ev}, heat of water evaporation, J/kg; α_c, coefficient of convective heat exchange, W/(m^2·K); T_{ss}, temperature of the soil surface, $^{\circ}$C; T_a, temperature of air at a height of 2 m, $^{\circ}$C; e_{ss}, specific humidity of air on the soil surface; e_a, specific humidity of air at a height of 2 m; V, wind velocity, m/sec; K_s, coefficient of the cloud amount for shortwave radiation; r, albedo of the soil surface; σ, Stefan–Boltzmann constant ($\sigma = 5.67 \cdot 10^{-8}$ W/(m^2·K^4)); I, overall solar radiation, W/m^2; I^*, solar constant ($I^* = 1.26$ kW/m^2); K_{lg}, coefficient of the cloud amount for longwave radiation; d, absorptivity of the soil; B_A, flux of opposite radiation of the atmosphere, W/m^2; B_0, soil radiation, W/m^2; h_{sun}, height of the sun above the horizon, deg; S, declination of the sun, deg; Π, period of rotation of the earth (24 h); ψ, geographic latitude of the locality, deg; D, day of the year; t_m, time reckoned from midday, h; τ_f, parameter of the turbidity of the atmosphere ($\tau_f = 2.4$). Subscripts: eff, effective; w, moisture; sk, skeleton; φ, evaporation and condensation of moisture; v, vapor; mat, matrix; R, radiation; c, convection; T, temperature; y, space coordinate along the Y axis; x, space coordinate along the X axis; ev, evaporation; ss, soil surface; a, air; sun, sun; sh, short; lg, long; m, midday; f, turbidity; H corresponds to the level of groundwater H.

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