DESCRIPTION OF HEAT AND WET EXCHANGE OF AN ATMOSPHERE WITH AN UNDERLYING SURFACE IN HYDRODYNAMICAL ATMOSPHERIC MODEL COUPLED WITH LAND MODEL

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The new approach to setting boundary conditions on the underlying surface in coupled atmosphere-land models is adduced, it has no artificial closings and correctly describes feedback - mutual influence of a surface and atmosphere. The algorithm of realization of this approach in application to a surface non-covered or covered by snow is described. For the first time in a large-scale model of a ground the influx of latent freezing-melting heat is taken into account. The results of numerical experiments are represented.

The description of a heat both moisture exchange between an atmosphere and underlying land surface is an extremely difficult task because of a variety of kinds of underlying surface and complexity of processes occurring on it. It is necessary to use plenty of thermal parameters describing the given surface. It is difficult to describe some processes on a surface, for example, processes in a vegetative cover, with the help of differential equations. It is also the difficulty, that the task is nonclosed. It is possible to determine fluxes of heat and moisture on a surface only with the help of artificial closing equations, if we don't solve the heat and moisture diffusion equations in the ground. In hydrodynamical atmospheric models various parametrisation formula and algorithms are used for account of values describing the heat and wet exchange between an atmosphere and a surface: methods of account of a surface temperature, wetness of ground, the heat flux in a ground, inner and exterior water drain, infiltration of a moisture, height of a snow cover [1]. In soil physics and agricultural meteorology the tasks of the description of processes in ground with the help of the equations of thermodynamics of irreversible processes are developed in details. The joint transport of heat and moisture, latent heat fluxes, change of salts concentrations are described. The plenty of various thermal soil characteristics is used when solving this task [3,4]. The transport of heat in a snow cover, melting and accumulation of snow are also considered. The atmosphere thus is considered as the external influencing factor, the feedbacks are not taken into account. Recently in some hydrodynamical models a task of the description of heat and moisture exchange of an atmosphere with an underlying surface both transport of heat and moisture in a ground are solved in common. In this case setting of a problem is most correct from the point of view of physics, but there is a difficulty connected with nonlinear boundary conditions at a level of a surface [6,8].

The seasonal temperature oscillations are being distributed in ground to depth of several meters. While modeling the heat and moisture transport in a ground it is good to put the bottom boundary condition on the depth, where temperature oscillations decay, and temperature is constant, but thus to take into account an arrangement of the top boundary of underground waters, if it is known [4].

The heat and moisture diffusion equations [3,4,6] can be used to construct the large-scale model of heat and moisture transport in a ground coupled with the atmospheric model.

At large-scale modeling there is no opportunity to describe in details the process of snow melting, therefore a balance method is used [4].

It is possible to use the equation of the heat balance for a thin surface layer of a ground, in which solar radiation is absorbed [2], and the equation of balance of a moisture on the surface as boundary conditions between an atmosphere and ground.

In models of an atmosphere turbulent heat and moisture fluxes inside a layer of constant fluxes are calculated, as a rule, with the help of special algorithms using: temperature and humidity on a surface; temperature, humidity and velocity at the bottom calculating level, which is set usually on the top boundary of a layer of constant fluxes.

It is very difficult to describe with the help of differential equations the influence of vegetation on heat and wet exchange of an atmosphere with ground. The influence of vegetation, as well as influence of horizontal inhomogenities of an underlying surface of small scale, were out of frameworks of our research.

The algorithm described below was externalized within the framework of hydrodynamical model of an atmosphere developed in RSHMU. We don't adduce here the equations of model and algorithms of account of radiation and turbulent fluxes because of their hugeness. The domain of the model covers Northern Hemisphere.

The temperature and humidity fields are three-dimensioned. However the vertical gradients in a boundary layer of air, as well as in an underlying ground, are much larger that horizontal ones. Therefore in this case it is possible to consider that processes of heat and wet exchange are one-dimensional and to carry out the accounts separately for each point of a horizontal grid. Let us set the vertical coordinate for solving of our problem by the following way: the level $z = 0$ is located on an underlying surface; the levels located under the surface will be negative. If it is snow on a surface, we move a level $z = 0$ on a surface of the snow and consider snow and ground to be one continuity, thermal properties of which depend on coordinate. In this case temperature of a surface have the same physical meaning.

The ground can have various qualitative characteristics: it can be frozen or unfrozen, it can be covered or not covered with snow. On its surface there can also pass or not pass various processes: the infiltration of precipitation dropped, accumulation and dissolution of snow, freezing and melting of the ground. Therefore here it is convenient at first to formulate basic equations, and then to add specializing blocks accounting for various qualitative characteristics and processes.

For unfrozen ground, on which surface doesn't pass any processes, equations of heat and wet transport with assumptions mentioned can be submitted as:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \lambda \frac{\partial T}{\partial z}, \quad \frac{\partial W}{\partial t} = D \frac{\partial^2 W}{\partial z^2}, \tag{1}$$

where $T(z,t)$, $W(z,t)$ - a temperature and mass wetness of the ground, ρ, c, λ - density, specific thermal capacity, heat conductivity of the ground respectively, D - the wet diffusion coefficient in the ground. The bottom boundary conditions we put on the level z_f, down to which seasonal temperature oscillations are being distributed:

$$T\big|_{z=z_f} = T_f, \quad \left.\frac{\partial W}{\partial z}\right|_{z=z_f} = 0, \tag{2}$$

where T_f - given (fixed) temperature on the level z_f. The boundary condition for wetness we have put, meaning that, we don’t know the depth of underground waters. If the level of underground waters is known and z_f is above the capillary zone of underground waters, the boundary condition also looks like (2). Differently it is necessary to put a condition of saturation on the top boundary of a capillary zone. We use the equations of balance of heat and moisture on a surface as top boundary conditions:

$$R\left(T\big|_{z=0}\right) - H\left(T\big|_{z=0}\right) - \lambda \frac{\partial T}{\partial z} - LE\left(T\big|_{z=0}, W\big|_{z=0}\right) = 0, \tag{3}$$

$$\gamma \left.\frac{\partial W}{\partial z}\right|_{z=0} - E\left(T\big|_{z=0}, W\big|_{z=0}\right) = 0, \tag{4}$$

where $R\left(T\big|_{z=0}\right)$ - the radiation balance of underlying surface, $H\left(T\big|_{z=0}\right)$ - the turbulent heat flux in the atmosphere, $E\left(T\big|_{z=0}, W\big|_{z=0}\right)$ - the turbulent wet flux in the atmosphere (evaporation), L - the latent heat of condensation, γ - the density of the ground skeleton. Functions $R\left(T\big|_{z=0}\right)$, $H\left(T\big|_{z=0}\right)$, and $E\left(T\big|_{z=0}, W\big|_{z=0}\right)$ connect the atmospheric model with the ground model, their values can be received from the values of $T\big|_{z=0}$ and using corresponding algorithms and meanings of some variables from atmospheric model. It is important to note, that these functions are non- linear. As the top boundary condition is non-linear, we solve the problem by numerical methods using of iterative process.

When the ground temperature falls below 0^{o}C, water in pores freezes, and at further increasing of temperature the ice is melting. At the front of freezing-melting the additional source of latent heat takes place. The front itself (which has depth $z=\xi$) is mobile (there may be several such fronts). At the front we put boundary conditions [5]:

$$T\big|_{z=\xi+0} = T\big|_{z=\xi-0} = T^*, \tag{5}$$

$$\lambda_1 \frac{\partial T}{\partial z}\bigg|_{z=\xi-0} - \lambda_2 \frac{\partial T}{\partial z}\bigg|_{z=\xi+0} = \tilde{L}\rho\left[W\big|_{z=\xi} - W_0\right]\frac{d\xi}{dt}, \tag{6}$$

where $T^* = 273K$, $\frac{d\xi}{dt}$ - the velocity of moving front, λ_1 and λ_2 - heat conductivity of unfrozen and frozen ground, $\tilde{L}$ - latent heat of ice melting, W_0 - the amount of unfrozen moisture, may be taken from the experimental data [4]. This problem in mathematics is known as Stephan problem. As far as the equations are being solved numerically, it is convenient to use Dirac δ -function [5]; it is can be "spread" along the temperature interval $\Delta = T - T^*$ and approximated by pseudo-delta-function $\delta\left(T - T^*, \Delta\right)$. We approximate δ - function by this way:

$$\delta\left(T - T^*, \Delta\right) = \begin{cases} \frac{1}{2\Delta}, & \left|T - T^*\right| \le \Delta \\ 0, & \left|T - T^*\right| > \Delta \end{cases}. \tag{7}$$

Then the first equation of system (1) can be written:

$$\tilde{c}\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\tilde{\lambda}\frac{\partial T}{\partial z}, \tag{8}$$

where

$$\tilde{\lambda} = \begin{cases} \lambda_1, & T < T^* - \Delta \\ \lambda_2, & T > T^* + \Delta \\ 0, & T \in \left[T^* - \Delta, T^* + \Delta\right] \end{cases}, \tag{9}$$

$$\tilde{c} = c' + \frac{1}{\rho}\tilde{L}\left[W\big|_{z=\xi} - W_0\right]\delta\left(T - T^*, \Delta\right), \tag{10}$$

$$c' = \begin{cases} c_1, & T < T^* \\ c_2, & T > T^* \end{cases}, \tag{11}$$

c_1 and c_2 - the specific thermal capacity of unfrozen and frozen ground.

If the surface of the ground is covered with snow it is possible to use the same equations (1) for modeling processes of heat and moisture transport in snow both ground if we enter the coordinate system, as it was described above. The domain and some boundary conditions change and various thermal characteristics of ground and snow are to be taken into account. Height of snow l depends on time, therefore the coordinate system will be "mobile" and the domain for the equation of heat transport will be depend on time. At the numerical approach this problem can be overcome.

If the liquid precipitation drops on unfrozen ground, we find depth, on which the water infiltrates, using the equation [4]:

$$\int_0^h W(t,z)dz + Q = W_{HB} \cdot h \,, \tag{12}$$

where $W(t,z)$ - the wet of the ground before precipitation, W_{HB} - the least wet capacity of the ground, $Q = P - N$ - the quantity of infiltrating water, P - precipitation, N - exterior water drain (depends on the precipitation intensity and existence of slopes). The equation (12) is solved numerically. If the infiltration goes down to depth, greater than our domain, we consider, that the "spare" moisture forms an internal drain. Further we change a profile of humidity from above down to the depth found h: $W = W_{HB}$.

The process of accumulation of snow is described by the formula:

$$\frac{dl}{dt} = Q_{SOL} \big/ \rho_{sn} \,, \tag{13}$$

where Q_{SOL} - solid precipitation, ρ_{sn} - the snow density.

The process of snow melting takes place, when the temperature in snow increases up to T^*. The change of thickness of a snow cover because of melting and amount of thawed water can be defined using the equation of thermal balance of a snow layer at melting:

$$\tilde{L}\rho_{sn}\frac{dl}{dt} = \tilde{L}\rho_w\frac{d\omega}{dt} = R(T^*) - H(T^*) - \lambda\frac{\partial T}{\partial z} - \left(L + \tilde{L}\right)E(T^*). \tag{14}$$

For carrying out the numerical decision of the equations of heat and moisture diffusion we shall enter a non-regular depths grid (5 layers). If it is snow on a ground, we enter new levels inside snow, then it is necessary to re-count the meaning of coordinate gridpoints: z' - coordinate of gridpoints of a new grid. It is known that at the numerical decision of the equations of heat and moisture diffusion it is necessary to use the implicit numerical scheme [5]. Therefore at the numerical decision of the equations (1) the implicit scheme of the directed forward differences on time and central differences for second derivative on space is used. Then the system of equations in finite differences will be:

$$A_i U_{i-1}^{s+1} - C_i U_i^{s+1} + B_i U_{i+1}^{s+1} = -F_i \,, \tag{15}$$

where

$$\begin{aligned}
A_i &= (\beta_i + \beta_{i-1})\Delta t / \alpha_i / (z'_i - z'_{i-1}) / (z'_{i+1} - z'_{i-1}) \,, \\
B_i &= (\beta_{i+1} + \beta_i)\Delta t / \alpha_i / (z'_{i+1} - z'_i) / (z'_{i+1} - z'_{i-1}) \,, \\
C_i &= A_i + B_i + 1 \,, \\
F_i &= U_i^s \,, \\
\alpha &= \begin{vmatrix} \rho\tilde{c} \\ 1 \end{vmatrix}, \quad \beta = \begin{vmatrix} \lambda \\ D \end{vmatrix}, \quad U = \begin{vmatrix} T \\ W \end{vmatrix},
\end{aligned} \tag{16}$$

i – the number of depth layer, *s* – the number of time step.

Here α_i and β_i depends on number of the layer i; if $z_i' < l^s$, they are characteristics of ground, if $z_i' \geq l^s$, the characteristics of snow are taken into account. For the moisture diffusion equation the coordinates of gridpoins are constant, $z_i' = z_i$, and α_i and β_i – the ground characteristics. The system of equations (15) is a thee-diagonal matrix, and it can be solved by the sweep method.

For the equations of heat and moisture diffusion it is necessary to put various boundary conditions for various kinds of a surface. As an example we should describe setting of boundary conditions and algorithm of the decision of the equation of heat and moisture diffusion on unfrozen surface which is not covered with snow. On the bottom boundary the conditions in discrete form with application of finite differences will be:

$$T_6^{s+1} = T_f, \quad W_5^{s+1} = W_4^{s+1}, \tag{17}$$

on the top boundary:

$$T_1^{s+1} = T_2^{s+1} - \frac{z_2}{\lambda} D1^{s+1}, \quad W_1^{s+1} = W_2^{s+1} - \frac{z_2}{\gamma} D2^{s+1}, \tag{18}$$

where

$$D1^{s+1} = R\left(T_1^{s+1}\right) + H\left(T_1^{s+1}\right) + E\left(T_1^{s+1}, W_1^{s+1}\right), \tag{19}$$

$$D2^{s+1} = E\left(T_1^{s+1}, W_1^{s+1}\right). \tag{20}$$

The system of equations (15)-(20) is closed, but the conditions (18)-(20) are nonlinear, $D1^{s+1}$ and $D2^{s+1}$ depend on T_1^{s+1} and W_1^{s+1}, besides, $D1^{s+1}$ and $D2^{s+1}$ depend on temperature and wetness on the first atmosphere level. That is why we are necessitated to realize rather complicated iteration process: we set the initial approximation meanings $T_1^{s+1,\nu_1=1} = T_1^s$, $W_1^{s+1,\nu_2=1} = W_1^s$ (ν_1 and ν_2 - the number of iterations on temperature and wetness); we account $D1^{s+1,\nu_1=1}$ and $D2^{s+1,\nu_1=1}$ according to them; then we solve the system (15)-(18), and we find vectors $T^{s+1,\nu_1=2}$ and $W^{s+1,\nu_2=2}$, as well as $T_1^{s+1,\nu_1=2}$ and $W_1^{s+1,\nu_2=2}$; we account $D1^{s+1,\nu_1=2}$ and $D2^{s+1,\nu_1=2}$ according to them and solve the system (15)-(18) again, etc. Iterations are carried out since

$$\max\left|T_1^{s+1,\nu_1+1} - T_1^{s+1,\nu_1}\right| \leq \varepsilon_1, \quad \max\left|W_1^{s+1,\nu_2+1} - W_1^{s+1,\nu_2}\right| \leq \varepsilon_2. \tag{21}$$

It is important to note, that at use of this algorithm the radiation block and block of account of fluxes in a boundary layer in atmospheric model should be solved implicitly.

Numerical experiments, which were carried out, have shown the following:

- The iterative process which is necessary in the given statement of the problem for the correct description of heat and wet exchange of an atmosphere with an underlying surface at using hydrodynamic model, coupled with model of a ground, converges.
- The iterative process converges much more slowly above a ground covered with snow, because of small heat conductivity of snow.

- The initial meanings of disparity are great enough: for temperature they make 4-6°C for the ground which is not covered with snow, and 7-9°C for a ground covered with snow, and for wetness 2-4 %.
- For convergence there are necessary 12-14 iterations on temperature above a ground covered with snow, and 6-8 iterations on temperature above a ground not covered with snow.
- It is rational to include the iterations on wetness after some convergence on temperature is achieved. In this case 3-4 iterations on humidity are required only.
- The iterations converge more slowly at the day-time at those points, where the condensation takes place, and at the night-time at those points, where the evaporation takes place. It corresponds to physics of process and is explained that in the given situations radiating fluxes and the fluxes of latent heat have one sign.
- The changes of temperature in ground because of latent heat are essential and make the tenth parts of degree. In a situation, when the front of freezing-melting is close to the surface, it renders significant influence on meanings of temperature on a surface.

The large meanings of the disparity in the beginning of iterations and different speed of convergence of iterative process in various meteorological situations, from our point of view, tells us about following. The interactivity, essential mutual influences both atmospheres on a ground and ground on an atmosphere, takes place. Therefore using of various artificial closing receptions for account of fluxes and tendency of temperature on the surface of ground results to significant loss of accuracy. In this case we actually describe or only influence of atmosphere on a ground, or only influence of ground on an atmosphere. Linearization of the top boundary condition leads to the same results. The correct statement of a problem with use of iterations allows us to describe processes of an exchange with the greater accuracy.

The influxes of heat because of latent heat of freezing-melting in a ground are not taken into account in models of a ground coupled with an atmosphere models at modeling on the large territories. However they appreciably influence on changes of temperature in ground. This process is especially important, when the freezing-melting front is near to a surface. Therefore the account of these influxes in model of a ground is rational.

REFERENCES:

1. Курбаткин Г.П., Дегтярев А.И., Фролов А.В. Спектральная модель атмосферы, инициализация и база данных для численного прогноза погоды. – СПб., Гидрометеоиздат, 1994, 182с.
2. Матвеев Л.Т. Курс общей метеорологии. – Л., Гидрометеоиздат, 1984, 751с.
3. Нерпин С.В., Чудновский А.Ф. Энерго- и массообмен в системе растение-воздух-почва. - Л., Гидрометеоиздат, 1975, 375с.

4. Палагин Э.Г. Математическое моделирование агрометеорологических условий перезимовки озимых культур. - Л., Гидрометеоиздат, 1981, 190с.
5. Тихонов А.Н., Самарский А.А. Уравнения математической физики.- М., ‘Наука’,1972, 734с.
6. Description of the NCAR Community Climate Model (CCM-2).- NCAR/TN-382+STR NCAR Technical Note, June, 1993, 108pp.
7. Pan H.-L. A Simple Parametrization Scheme of Evapotranspiration over Land for the NMC Medium-Range Forecast Model. - Mon.Wea.Rew., vol.118, 1990, p.2500-2512.
8. Simulation of the Present-day Climate with the ECHAM Model: Impact of Model Physics and Resolution. – Max-Planck-Institut fur Meteorologie, rep. N 93, Hamburg, October 1992.

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