MODELS OF VERTICAL ENERGY AND WATER TRANSFER WITHIN THE "SOIL – VEGETATION – ATMOSPHERE" SYSTEM

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Contents

Summary

Soil – Vegetation/snow cover - near surface Atmosphere System (SVAS) plays a special role in the formation of climatic, hydrological and biotic processes, being "the point of coupling" of the three major global dissipative processes: circulation of the atmosphere, the hydrological cycle and turnover of bioelements in terrestrial ecosystems. This underlines the importance of studying and modeling the processes of energy and mass exchange, which take place at the land-atmosphere interface, namely, in SVAS. Since the 1970s considerable attention has been focused on adequate modeling of energy and water transfer occurring in SVAS. Such models represent one-dimensional models named Soil – Vegetation – Atmosphere – Transfer (SVAT) models. The models differ from one another by treated processes and by their parameterizations that results in differences in models' structure, complexity and discretization of the modeled object. In general, the more advanced SVAT models treat, in more or less details, the following processes of vertical energy and water transfer and conversion: reflection of incoming shortwave radiation; the land surface heating and thermal emission; turbulent heat transfer from the land surface to the atmosphere; interception of

rainfall/snowfall by the vegetation canopy; evapotranspiration (including transpiration by plants, soil/snow evaporation/sublimation, evaporation of intercepted precipitation); formation of snowpack on the ground and on the trees' crowns (including snow accumulation, snow evaporation, snowmelt, water yield of snow cover, refreezing of melt water); formation of surface and subsurface runoff; water infiltration into a soil; soil heat and water transfer; phase changes of water in a soil; interaction between soil water and groundwater. The main steps in the model construction are studying the processes of energy and water exchange in SVAS and revealing the main processes to be modeled, mathematical formalization of these processes and construction of calculation algorithm, development of model code, estimation of model parameters and initial conditions, collecting the forcing data to drive the model, validation of model outputs against observations.

1. Soil-Vegetation/snow Cover- Atmosphere System (SVAS)

In accordance with the intensity of development of the fields of science, the 18th century is often called the century of Newton, the 19th – the century of Darwin and the 20th – the century of Vernadskiy, who developed a theory of the biosphere – a specific envelope of the planet, organized by life. It is in the 20th century that the present rapid development of different sciences on the Earth's biosphere started. Tremendous progress in the field of the applied mathematics and computers, as well as development of the language of physical-mathematical modeling, universal for many researchers, has led to the application of Vernadskiy's thesis about the unity and interconnection of nature as has been reflected in interconnection and interpenetration of sciences and has enabled complex mathematical description of the main processes of the biosphere. These processes represent, first of all, global circulations of different substances governed by solar energy. Origination of such circulations is inevitable on the planet, since the only structure-forming response of the Earth, as a limited (in terms of its volume and the amount of substance) system, to the continuous impact of free energy, may be organization of its own energy flow, which neutralizes the external energy impact on the basis of matter turnover. Thus, the solar radiation energy reaching the Earth sets in motion all cycles on the planet, the most intensive among which are the atmospheric circulation, the hydrological cycle and the circulation of bioelements (Figure 1).

It should be noted that on the land, the conversion of solar radiation to the other forms of energy occurs within a very thin planetary layer, practically on the boundary between the atmosphere and the lithosphere. This is a layer of coupling of all four components of the biosphere: the atmosphere, the upper part of the lithosphere, the hydrosphere and the terrestrial living matter. The thickness of this layer, called "a film of life" by V.I. Vernadskiy, is very slight: it does not exceed several tens of meters over the ground and does not go down lower than several meters. However, this "film of life" or, as it is called in climatology, meteorology and hydrology, S*oil - Vegetation and (or) snow cover - near surface Atmosphere System* (*SVAS*) plays a special role in the formation of climatic, hydrological and biotic processes. *SVAS is "the point of coupling" of the three aforementioned global dissipative structures: circulation of the atmosphere, the hydrological cycle and turnover of bioelements in terrestrial ecosystems* (Figure 1). Two important issues should be mentioned here. First, since solar energy, which sets in motion these structures, converting to the other forms of energy in the same “point”, it is here that both the intensity and the character of temporal dynamics of the indicated dissipative structures are in fact controlled. Second, all three structures are interconnected and mutually dependent. These circumstances warrant a study and adequate description of the complex physical mechanism of the processes of heat and mass exchange within the SVAS.

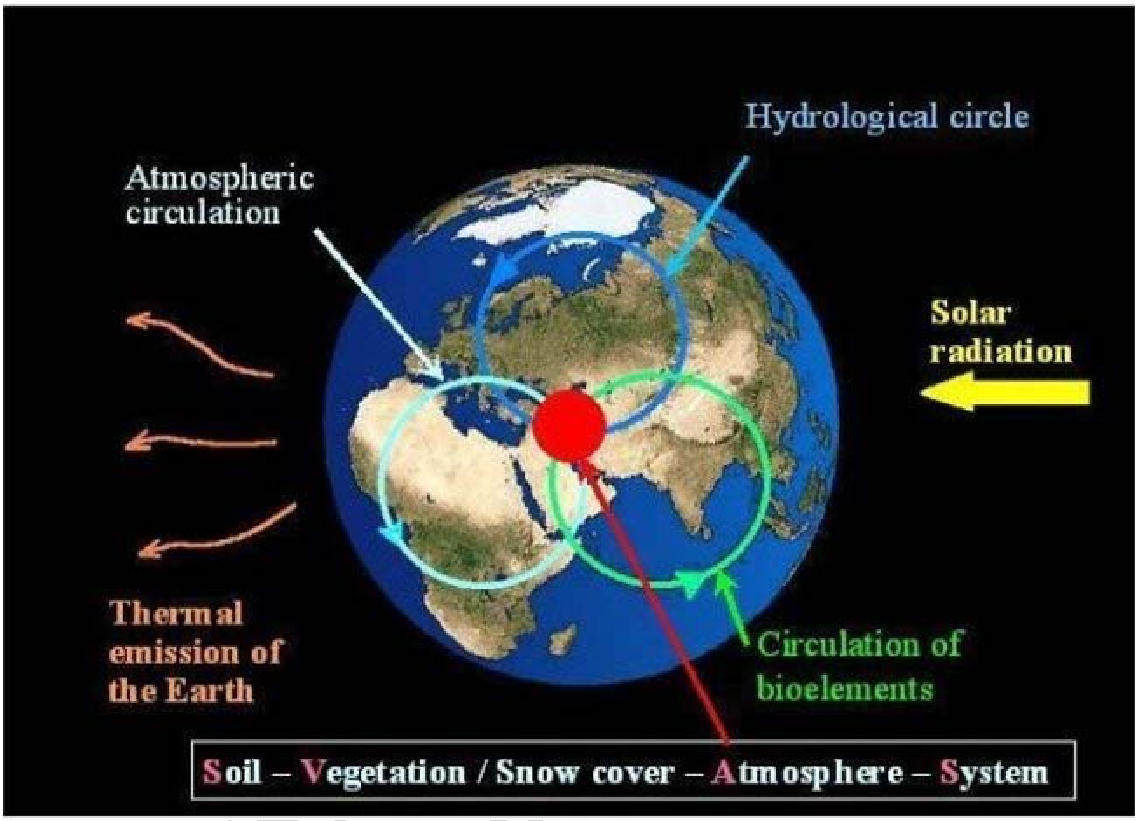

Figure 1. Major (with respect to energy intensity) global cycles on the Earth and location of the soil-vegetation/snow cover-atmosphere system.

2. Energy and Water Exchange in SVAS

2.1. Energy Transfer and Conversion in SVAS

In accordance with thermodynamics, two processes associated with energy may occur in SVAS: energy conversion from one form to another and energy transfer. In the absence of work, heat is the only mechanism by which energy can be transferred to or from the system. This heat transfer may occur by the mechanisms of conduction, convection and radiation. Knowledge of these mechanisms is necessary to formalize heat fluxes in terms of mathematical equations.

To describe these processes let us consider the interface soil/vegetation/atmosphere as a layer with the thickness equal to the height of vegetation/snow or zero in the case of bare soil. This layer receives the energy at the upper boundary in the form of solar radiation $R_S\downarrow$ and thermal emission of the atmosphere $R_L\downarrow$ (Figure 2). These radiation fluxes are usually referred to as incoming (or downward) shortwave and longwave radiation, respectively. Incoming solar radiation $R_{\mathrm{S}}\downarrow$, which consists of direct radiation coming to a horizontal surface (I) and diffuse radiation (D)

$$R_{\mathrm{S}}\downarrow = I + D \qquad (1)$$

is partially reflected back to the atmosphere. The reflected radiation is also called the upward (or outgoing) shortwave radiation $R_{\mathrm{S}}\uparrow$. The amount of reflected radiation depends on the surface albedo α that characterizes the reflectivity of the surface and represents the ratio between outgoing and incoming shortwave radiation fluxes. Thus, $R_{\mathrm{S}}\uparrow$ can be presented as:

$$R_{\mathrm{S}}\uparrow = \alpha R_{\mathrm{S}}\downarrow \qquad (2)$$

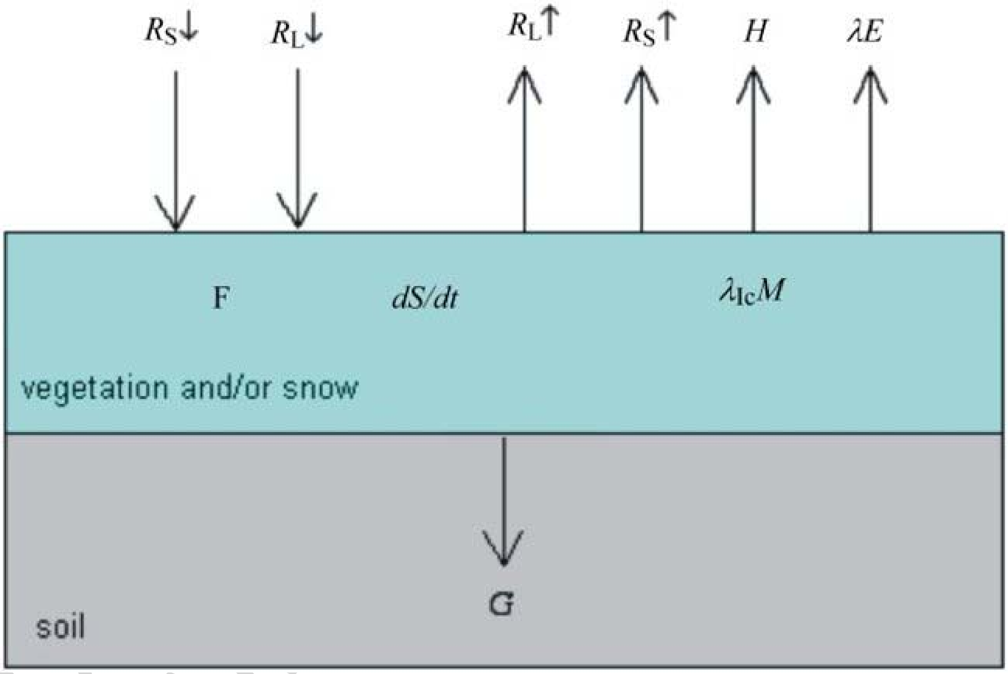

Figure 2. Shematic presentation of energy transfer and conversion at the land surface - atmosphere interface

Incoming radiation, both longwave and shortwave (which was not reflected to the atmosphere), turns into thermal energy, energy of phase changes and energy of chemical bonds of primary biological structures as a result of photosynthesis. The thermal energy partly goes back to the atmosphere in the form of thermal emission of the land surface $R_{\mathrm{L}}\uparrow$ and sensible heat flux H; the rest goes to a soil as a ground heat flux G and is absorbed by vegetation/snow, changing their heat storage $\partial S/\partial t$. The energy of phase transitions participates in transformations of water, contained in SVAS, from one phase state (liquid, solid, or gaseous) into another. The processes associated with phase transitions at the land surface are as follows: evaporation (or sublimation if the water exists at the surface in the solid phase) and snowmelt. The opposite processes are condensation and water freezing, respectively. Energy consumed for evaporation/sublimation or released from condensation is named latent heat λE (positive for evaporation/sublimation) that is usually distinguished from the energy spent for snowmelt or released from water freezing $\lambda_{\mathrm{Ic}} M$ (positive for melting). Here, E is the rate of evaporation, M is the rate of smowmelt, $\lambda = \lambda_{\mathrm{Ic}} + \lambda_{\mathrm{W}}$ is the specific heat of phase change solid $\rightarrow$ gas, equals to the sum of specific heat of ice fusion λ_{Ic} and specific heat of vaporization λ_{W}, $\lambda = \lambda_{\mathrm{W}}$ for evaporation and $\lambda = \lambda_{\mathrm{Ic}} + \lambda_{\mathrm{W}}$ for sublimation. The energy consumed by photosynthesis F is very small (< 1% of the solar energy received by plants), however, it is this energy that maintains primary biological production and, finally, the existence of vegetation. The above described can be expressed in the form of the energy balance equation of the land surface layer (in accordance with the first law of thermodynamics stating that the energy of a closed system is conserved):

$$R_{\mathrm{S}} \downarrow - R_{\mathrm{S}} \uparrow + R_{\mathrm{L}} \downarrow = R_{\mathrm{L}} \uparrow + H + \lambda E + \lambda_{\mathrm{Ic}} M + G + \partial S / \partial t + F \qquad (3)$$

It should be noted that radiation fluxes are positive when they are directed from the atmosphere to the land surface, non-radiation fluxes are positive when they are directed from the land surface (to the atmosphere or to a soil).

Sum of incoming and outgoing shortwave and longwave radiation fluxes in Eq.(3) represents net radiation on the upper boundary of SVAS R_{n}, which consists of shortwave R_{nS} and longwave R_{nL} components, each of the two is a difference between incoming (downward) and outgoing (upward) fluxes of shortwave and longwave radiation, respectively:

$$R_{\mathrm{n}} = R_{\mathrm{nS}} + R_{\mathrm{nL}} = R_{\mathrm{S}} \downarrow - R_{\mathrm{S}} \uparrow + R_{\mathrm{L}} \downarrow - R_{\mathrm{L}} \uparrow \qquad (4)$$

The thermal emission of the land surface $R_{\mathrm{L}} \uparrow$, which is also called upward longwave radiation outgoing from the land surface to the atmosphere, can be expressed according to the Stefan-Boltzmann law by the following formula:

$$R_{\mathrm{L}} \uparrow = \sigma \varepsilon \, T_{\mathrm{S}}^4 \qquad (5)$$

where ε is the thermal emissivity of the land surface, σ is the Stefan-Boltzmann constant, T_{S} is the land surface temperature.

Taking into account Eqs. (2) and (5), the net radiation may be presented as follows:

$$R_{\mathrm{n}} = (1-\alpha) R_{\mathrm{S}} \downarrow + R_{\mathrm{L}} \downarrow - \sigma \varepsilon T_{\mathrm{S}}^4 \qquad (6)$$

The quantities α and ε are characteristics of the land surface. Albedo has annual and daily course, thermal emissivity of different types of the land surface is close to 1 and in model simulations it is usually assumed to be equal to 1. Net radiation varies depending on the latitude, natural conditions, and characteristics of the land surface. It also has annual and daily course. In the boreal zone, R_n is positive during diurnal hours and negative at night; in its annual course, it is positive in summer and negative in winter.

The heat balance Eq. (3) may be rewritten in its more usual form with accounting for Eq.(4) and neglecting of F

$$R_\mathrm{n} = H + \lambda\, E + \lambda_\mathrm{Ic} M + G + \partial S / \partial t \qquad (7)$$

The sensible heat flux H (it is called sensible to distinguish from latent heat spent for phase changes) represents heat transfer by means of convection mechanism. Two types of convection are commonly distinguished, free convection, in which gravity and buoyancy forces drive the fluid movement, and forced convection. In the atmosphere, forced convection is generated by wind. In convection, fluid movement has a turbulent character. This means that the sensible heat flux H is a turbulent flux and may be formalized using equation for turbulent diffusion (which is analogous to molecular diffusion of the form):

$$H = -c_\mathrm{p} A_\mathrm{T} \frac{\partial \Theta}{\partial z} = -c_\mathrm{p} \rho k_\mathrm{T} \frac{\partial \Theta}{\partial z} = -c_\mathrm{p} \rho k_\mathrm{T} \left(\frac{\partial T}{\partial z} + \gamma_\mathrm{a} \right) \qquad (8)$$

where c_p is the specific heat capacity at constant pressure (J kg^{-1} K^{-1}), A is the coefficient of turbulent exchange for heat (kg s^{-1}m^{-1}), Θ is the potential air temperature, T is the air temperature (K), ρ is the air density (kg m^{-3}), k_T is the thermal diffusivity (m^{2}s^{-1}), γ_a is the dry-adiabatic gradient, z is the vertical coordinate (distance from the surface (m), positive upwards).

Ground heat flux G represents heat transfer in a soil by means of conduction mechanism and may be presented as follows

$$G = -\lambda_\mathrm{T} \frac{\partial T}{\partial z} \qquad (9)$$

where λ_T is the thermal conductivity, T is the soil temperature (K), z is the vertical coordinate (distance from the surface (m), positive downwards). In a soil, incoming heat is spent for changing its heat storage and for phase changes of soil water that can be expressed by the following equation

$$c_\mathrm{p} \rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left(\lambda_\mathrm{T} \frac{\partial T}{\partial z} \right) + I_\mathrm{F} \qquad (10)$$

Here, $c_\mathrm{p} \rho = C$ is the volumetric soil heat capacity which can be estimated as a weighted sum of the heat capacity of soil phases

$$C_{\mathrm{s}} = \left(1-\theta_{\mathrm{s}}\right)C_{\mathrm{m}} + \theta_{\mathrm{w}}C_{\mathrm{w}} + \theta_{\mathrm{Ic}}C_{\mathrm{Ic}} \tag{11}$$

where $C_i = c_{\mathrm{p}i}\rho_i\left(i = \mathrm{s,m,w,Ic}\right)$ is the volumetric heat capacity of *i*-th substance; the subscripts s, m, w and Ic refer to the whole soil, soil matrix, soil liquid water and ice, respectively; θ_{s} is the soil porosity; θ_{w} and θ_{Ic} are the soil water and ice contents, respectively. The heat capacity of soil air is neglected being three orders of magnitude smaller than that of the other phases. The term I_{F} in Eq.(10) corresponds to energy released from phase change of ice to water

$$I_{\mathrm{F}} = \begin{cases} 0 & \text{if} \quad T > 0 \\ \lambda_{\mathrm{Ic}}\rho_{\mathrm{Ic}}\dfrac{\partial\theta_{\mathrm{Ic}}(T)}{\partial t} & \text{if} \quad T \le 0 \end{cases} \tag{12}$$

The term I_{F} may be rearranged to the left-hand side of the Eq.(10). In this case, in the left side, the so-called effective heat capacity $C_{\mathrm{s,eff}}$ is used instead of C_{s}

$$C_{\mathrm{s,eff}} = \begin{cases} C_{\mathrm{s}} - \lambda_{\mathrm{Ic}}\rho_{\mathrm{Ic}}\dfrac{\partial\theta_{\mathrm{Ic}}(T)}{\partial T} = C_{\mathrm{s}} + \lambda_{\mathrm{Ic}}\rho_{\mathrm{w}}\dfrac{\partial\theta_{\mathrm{w}}(T)}{\partial T} & \text{if} \quad T \le 0 \\ C_{\mathrm{s}} & \text{if} \quad T > 0 \end{cases} \tag{13}$$

Here, in the case of $T \le 0$, the last term in the right-hand side is associated with the fact that, in the frozen soil, the amount of ice and liquid water are connected with the total soil mass water content W by relation $W = \rho_{\mathrm{w}}\theta_{\mathrm{w}} + \rho_{\mathrm{Ic}}\theta_{\mathrm{Ic}}$ (it should be noted that there is always some amount of liquid water in the frozen soil). Using the concept of the effective heat capacity, Eq.(10) may be rewritten in the form of the heat transfer equation

$$C_{\mathrm{s,eff}}\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_{\mathrm{T}}\frac{\partial T}{\partial z}\right) \tag{14}$$

In the case of bare soil, short vegetation or snow, $\partial S/\partial t$ in Eq.(7) is usually omitted, in the case of high vegetation, it should be taken into account. It was noted that this term is especially important in the moments after the sun rise and before the sun set, when it is of the same order as R_{n}, however, it is generally neglected for daily averaging.

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