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Description of a land–air parameterization scheme (LAPS)

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Abstract

A land–air parameterization scheme (LAPS) describes mass, energy and momentum transfer between the land surface and the atmosphere. The scheme is designed as a software package, and can be run as part of an atmospheric model or as a stand-alone model. A single layer approach is chosen for the physical and biophysical scheme background. The scheme has seven prognostic variables: three temperature variables (the canopy vegetation, soil surface and deep soil), one interception storage variable, and three soil moisture storage variables. In the scheme upper boundary conditions are used: air temperature, water vapor pressure, wind speed, radiation and precipitation at a reference level within the atmospheric boundary layer. The sensible and latent heat are calculated using resistance representation. The evaporation from the bare soil is parameterized using an "α" scheme. The soil model part is designed as a three-layer model which is used to describe the vertical transfer of water in the soil.

1. Introduction

Recently, a large effort has been invested in coupling the land surface and the atmosphere in atmospheric, hydrological and ecological models. For that purpose a vast number of land surface parameterization scheme has been designed based on different concepts. Also, they have different level of complexity depending on the model where the scheme is incorporated. Comprehensive overviews of the achieved levels, future plans and recommendations in designing the land surface schemes can be found in Henderson-Sellers et al. (1993) and Shao et al. (1994).

The interaction of the land surface and the atmosphere, may be summarized as follows: interaction of vegetation with radiation, evaporation from bare soil, evapotranspiration which includes transpiration and evaporation of intercepted precipitation and dew, conduction of soil water through the vegetation layer, vertical water movement in the soil, runoff, heat conduction in the soil, momentum transport, effects of snow presence and freezing or melting of soil moisture. Consequently, the processes parameterized in the land surface schemes can be divided into three sections: subsurface thermal and hydraulic processes, bare soil transfer processes and canopy transfer processes.

This paper describes the biophysical scheme named LAPS (Land–Air Parameterization Scheme), developed through the joint efforts of the University of Novi Sad and University of Belgrade. The scheme is designed as a software package which can be run as a part of an atmospheric model or as a stand-alone model. The vegetation in the model is treated as a block of constant density porous material sand-

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wiched between two constant stress layers with an upper boundary (the height of canopy top) and a lower boundary (the height of canopy bottom).

The design of the scheme is based on papers by Sellers et al. (1986); Dickinson et al. (1986); Mihailović (1990); Mihailović et al. (1993) and Mihailović and Jeftić (1994).

A detailed description and explanation of the schemes's structure, governing equations, the representation of energy fluxes and radiation, the parameterization of aerodynamic canopy characteristics, resistances and model hydrology will be given in the following sections.

2. Scheme structure and basic equations

The LAPS scheme uses the morphological and physiological characteristics of the vegetation community for deriving the coefficients and resistances that govern all the fluxes between the surface and atmosphere.

The model has seven prognostic variables: three temperatures (canopy, soil surface and deep soil); interception store for canopy; and three soil moisture stores.

The prognostic equations for the canopy temperature, T_f, and the soil surface temperature, T_g and deep soil temperature T_d, are

$$C_f \frac{\partial T_f}{\partial t} = R_f^{net} - H_f - \lambda E_f \quad (1)$$

$$C_g \frac{\partial T_g}{\partial t} = R_g^{net} - H_g - \lambda E_g - G \quad (2)$$

$$\frac{\partial T_d}{\partial t} = 2C_g\left(R_g^{net} - H_g - \lambda E_g\right)/\sqrt{365\pi} \quad (3)$$

where C is the heat capacity, R^{net} the absorbed short wave and long wave radiation, H the sensible heat flux, λ the latent heat of vaporization, E the evapotranspiration rate and G the soil heat flux. The subscript f refers to the canopy, g to the soil surface. The soil heat flux is parameterized using "force-restore" method. The ground heat capacity C_g is parameterized following Zhang and Anthes (1982).

The prognostic equations for the water stored on the canopy, w_f, is

$$\frac{\partial w_f}{\partial t} = P_f - E_{wf}/\rho_w \quad (4)$$

where ρ_w is the density of water, P_f the water amount retained on the canopy, E_{wf} the evaporation of water from the wetted fraction of canopy. When the conditions for dew formation are satisfied, the condensed moisture is added to the interception store, w_f.

The parameterization of the soil moisture content is based on the concept of the three-layer model that was already supported by Sellers et al. (1986) and Mihailović (1991). The governing equations take the form:

$$\frac{\partial w_1}{\partial t} = \frac{1}{D_1}\left\{P_1 - F_{1,2} - \frac{E_g + E_{tf,1}}{\rho_w} - R_0 - R_1\right\} \quad (5)$$

$$\frac{\partial w_2}{\partial t} = \frac{1}{D_2}\{F_{1,2} - F_{2,3} - E_{tf,2}/\rho_w - R_2\} \quad (6)$$

$$\frac{\partial w_3}{\partial t} = \frac{1}{D_3}\{F_{2,3} - F_3 - R_3\} \quad (7)$$

where w_i is the volumetric soil moisture content in ith layer, P_1 the infiltration rate of precipitation into the upper soil moisture store, D_i the thickness of the ith soil layer, $F_{i,i+1}$ the water flux between i and $i+1$ soil layer, F_3 the gravitational drainage flux from recharge soil moisture store, $E_{tf,1}$ and $E_{tf,2}$ the canopy extraction of soil moisture by transpiration from the first and the second soil layer, respectively, R_o the surface runoff and R_i the subsurface runoff from the ith soil layer. Detailed description the foregoing terms will be given in the next sections.

Eq. (1)–(3) are solved by an implicit backward method, while Eq. (5)–(7) are solved using an explicit time scheme.

3. Representation of energy fluxes

Our treatment of the energy fluxes may be classified as the so-called "resistance" representation. This formulation is often used to describe the energy fluxes in an Ohm's law analog form:

$$\text{flux} = \frac{\text{potential difference}}{\text{resistance}} \quad (8)$$

Potential difference for sensible and latent heat fluxes can be expressed in terms of chosen prognostic

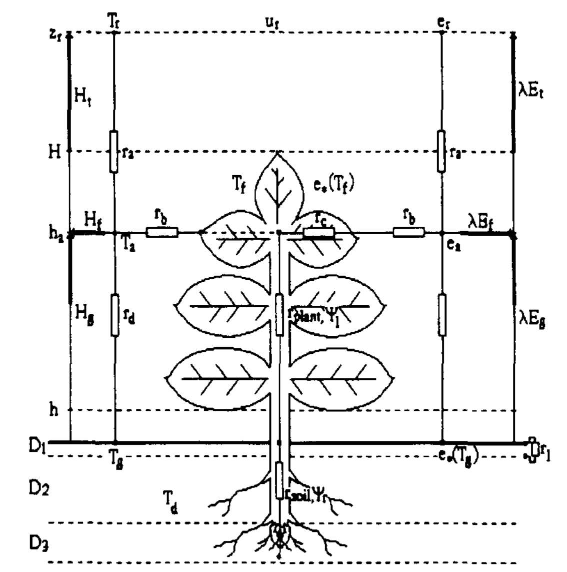

Fig. 1. LAPS schematic diagram of transfer pathways for latent and sensible heat fluxes.

variables, atmospheric boundary layer reference temperature and water vapor pressure in the canopy air space. Since resistances will be considered in the next section, here we will pay our attention to the physical background of the energy fluxes used in the model. The LAPS schematic diagram of transfer pathways for latent and sensible heat fluxes is shown in Fig. 1.

The latent heat flux from canopy vegetation to canopy air space is given by

$$\lambda E_{\mathrm{f}} = \left[e_*(T_{\mathrm{f}}) - e_{\mathrm{a}} \right] \left(\frac{w_{\mathrm{w}}}{r_{\mathrm{b}}} + \frac{1 - w_{\mathrm{w}}}{r_{\mathrm{b}} + r_{\mathrm{c}}} \right) \frac{\rho c_p}{\gamma} \tag{9}$$

where $e_*(T_{\mathrm{f}})$ is the saturation water vapor pressure at the canopy temperature T_{f}, e_{a} the water vapor pressure of the air at the canopy source height, w_{w} the wetted fraction of canopy, r_{b} the bulk boundary layer resistance for the canopy leaves, r_{c} the bulk stomatal resistance of the canopy leaves, ρ the density of air, c_p the specific heat of air at constant pressure and γ the psychrometric constant.

The sensible heat flux from canopy vegetation to canopy air space is given by

$$H_{\mathrm{f}} = 2(T_{\mathrm{f}} - T_{\mathrm{a}}) \frac{\rho c_p}{r_{\mathrm{b}}} \tag{10}$$

where T_{a} is the temperature of air at the canopy source height.

The latent and sensible heat fluxes from soil surface are parameterized as

$$\lambda E_{\mathrm{g}} = \frac{\rho c_p}{\gamma} \frac{\left[\alpha e_*(T_{\mathrm{g}}) - e_{\mathrm{a}} \right]}{r_{\mathrm{l}} + r_{\mathrm{d}}} \tag{11}$$

$$H_{\mathrm{g}} = \rho c_p \frac{T_{\mathrm{g}} - T_{\mathrm{a}}}{r_d} \tag{12}$$

where $e_*(T_{\mathrm{g}})$ is the saturation water vapor pressure at the soil surface temperature T_{g}, r_{l} is the bare soil surface resistance and r_{d} the aerodynamic resistance between the soil surface and the canopy source height. Parameter α is calculated according to Mihailović et al. (1993), where α is considered as a function of the volumetric soil moisture content of the top soil layer, w_{l}, and field capacity, w_{fc},

$$\alpha = \begin{Bmatrix} 1 - \left[(w_{\mathrm{fc}} - w_{\mathrm{l}})/w_{\mathrm{fc}} \right]^2 & w_{\mathrm{l}} \le w_{\mathrm{fc}} \\ 1 & w_{\mathrm{l}} > w_{\mathrm{fc}} \end{Bmatrix}. \tag{13}$$

The flux λE_{wf} from the wetted portion of foliage, with wetted fractions denoted by w_{w} according to Eq. (9) is

$$\lambda E_{\mathrm{wf}} = \left[e_*(T_f) - e_a \right] \frac{w_{\mathrm{w}}}{r_b} \frac{\rho c_p}{\gamma} \tag{14}$$

The fraction of the foliage that is wet, w_{w}, is parameterized according to Deardorff (1978) and Dickinson (1984).

Transpiration occurs only from dry leaf and it is only outward. This physiological process is parameterized with the equation:

$$\lambda E_{\mathrm{tf}} = \left[e_*(T_{\mathrm{f}}) - e_{\mathrm{a}} \right] \frac{1 - w_{\mathrm{w}}}{r_{\mathrm{b}} + r_{\mathrm{c}}} \frac{\rho c_p}{\gamma} \tag{15}$$

where E_{tf} is the transpiration rate from foliage. Dew formation occurs when $e_*(T_{\mathrm{f}}) \le e_{\mathrm{a}}$. In that case the condensed moisture is added to the surface interception store, w_{f}. The transpiration rate is zero under this condition.

Air within the canopy has negligible heat capacity, so the sensible heat flux from the canopy, H_{f}, and from the soil surface, H_{g}, must be balanced by the sensible heat flux to the atmosphere, H_{t}

$$H_{\mathrm{t}} = H_{\mathrm{f}} + H_{\mathrm{g}} = (T_{\mathrm{f}} - T_{\mathrm{r}}) \frac{\rho c_p}{r_{\mathrm{a}}} \tag{16}$$

where T_r is the air temperature at the reference level within the atmospheric boundary layer and r_a the aerodynamic resistance between canopy air space and reference level. Similarly, the canopy air is assumed to have zero capacity for water storage so that the latent heat flux from canopy air space to reference level in atmospheric boundary layer, λE_t, balances the latent heat flux from canopy vegetation to canopy air space, λE_f, and the latent heat flux from soil surface to the canopy air space, λE_g

$$\lambda E_t = \lambda E_f + \lambda E_g \frac{(e_a - e_r)}{r_a} \frac{\rho c_p}{\gamma} \tag{17}$$

where e_r is the water vapor pressure of the air at the reference level within the atmospheric boundary layer.

Diagnostic variables T_a and e_a were calculated from Eq. (16) and (17), using corresponding expressions for H_f, H_g, λE_f and λE_g.

4. Parameterization of radiation

The net radiation absorbed by the canopy, R_f^{net}, and the soil surface, R_g^{net}, is calculated as a sum of short and long wave radiative flux,

$$R_f^{net} = R_f^s + R_f^l \tag{18}$$

and

$$R_g^{net} = R_g^s + R_g^l \tag{19}$$

The short wave radiation absorbed by the canopy, R_f^s, and the soil surface, R_g^s, is:

$$R_f^s = R_0^s(\sigma_f - \alpha_f)\left[1 + (1 - \sigma_f)\alpha_g\right] \tag{20}$$

$$R_g^s = R_0^s(1 - \sigma_f)(1 - \alpha_g + \alpha_f \alpha_g) \tag{21}$$

where R_o^s is the incident downward directed short wave flux, assumed to be known as the forcing variable, α_g and α_f are the soil surface albedo and the foliage albedo, respectively, and σ_f is the vegetation fraction cover. The variability of ground albedo with soil wetness is parameterized in accordance with Idso et al. (1975). There is no distinction between direct and diffuse radiation and it is assumed that albedo does not vary with zenith angle. Both short wave and long wave radiation are reflected once between the soil surface and canopy.

The long wave radiative fluxes absorbed by the canopy, R_f^l, and the soil surface, R_g^l, are

$$\begin{aligned} R_f^l = {} & R_0^l \sigma_f \varepsilon_f - 2\sigma_f \varepsilon_f \sigma_B T_f^4 \\ & + \sigma_f \varepsilon_f \left[R_0^l (1 - \sigma_f)(1 - \varepsilon_g) \right. \\ & \left. + \sigma_f \varepsilon_f (1 - \varepsilon_g) \sigma_B T_f^4 + \varepsilon_g \sigma_B T_g^4 \right] \end{aligned} \tag{22}$$

$$\begin{aligned} R_g^l = {} & \varepsilon_g \left[R_0^l (1 - \sigma_f) + \varepsilon_f \sigma_f \sigma_B T_f^4 \right. \\ & \left. + \sigma_f \varepsilon_g (1 - \varepsilon_f) \sigma_B T_g^4 - \sigma_B T_g^4 \right] \end{aligned} \tag{23}$$

where σ_B is the Stefan-Boltzman constant, ε_f and ε_g the emissivities of the foliage and the soil surface respectively, and R_o^l the incident downward long wave radiation prescribed as the forcing variable.

5. Aerodynamic canopy characteristics and resistances

In the model the vegetation is represented as a block of constant density porous material sandwiched between two constant stress layers, the height of the canopy top, H and the height of the canopy bottom, h (Fig. 1).

The shear stress τ above the canopy was calculated according to the Monin-Obuhov theory where it has the form:

$$\tau = \rho\{ku_r/[\ln((z-d)/z_o)] + \Psi_M\}^2 \tag{24}$$

where ρ is the air density, u_r the wind speed at a reference height, z_r, within the atmospheric boundary layer, $k = 0.41$ the von Karman's constant, d the zero plane displacement height, z_o the roughness length and Ψ_M the stability adjustment function for momentum transport.

The shear stress within the canopy using the "K-theory" is expressed as

$$\tau = \rho K_m \frac{\partial u}{\partial z} \tag{25}$$

where K_m is the momentum transfer coefficient which is parameterized as

$$K_m = \sigma_s u \tag{26}$$

where σ_s is a constant and u the wind speed within the canopy. The constant σ_s is defined following Goudriaan (1977)

$$\sigma_s = i_w \left[\frac{4 w_d}{\pi L_d} \right]^{1/2} \tag{27}$$

where i_w is the relative turbulence intensity, w_d is the width of the square leaves and L_d the stem and leaf area density related to leaf area index, LAI, as $\mathrm{LAI} = L_d\,(H - h)$.

The wind speed inside the canopy is given by

$$u = u_H[\sinh(\beta z/H)/\sinh \beta]^{1/2} \quad (28)$$

where u_H is the wind speed at the canopy top. The extinction factor, β, depends on the plant morphology and is defined as

$$\beta = \left(\frac{C_d\,\mathrm{LAI}\,H}{2\sigma_s}\right)^{1/2} \quad (29)$$

where C_d is the leaf drag coefficient.

For the zero plane displacement height, d and roughness length, z_o, we calculated according to Goudriaan (1977):

$$d = H - \frac{1}{k}\left(\frac{\sigma_s H}{\beta}\right)^{1/2} \quad (30)$$

and

$$z_o = (H - d)\exp\left\{-\frac{H}{\beta(H - d)}\right\} \quad (31)$$

As we mentioned in Section 3 the fluxes in the model are calculated using aerodynamic and surfaces resistances. Corresponding electrical circuits with resistances are shown in Fig. 1. The resistances r_a, r_b and r_d are usually called aerodynamic resistances and they are equivalent to the integrals of inverse conductances over a specified length. In the case of the aerodynamic resistances, the conductances correspond to the turbulent transfer coefficient for heat and water vapor. Surface resistances r_c and r_l control water transfer through the plant–soil system.

The aerodynamic resistance r_a represents the transfer of heat and moisture from the canopy to reference level, z_r, and is calculated as

$$r_a = \frac{1}{k u_*}\ln\frac{z_r - d}{H - d} \quad (32)$$

where u_* is the friction velocity.

The area-averaged bulk boundary layer resistance, r_b, is calculated as

$$r_b = \frac{1}{u_H^{1/2}} P_s C_t \beta(\sinh \beta)^{1/4} \Big/ (L_d H)\int_{\alpha_w \beta}^{\beta} (\sinh y)^{1/4} \mathrm{d}y \quad (33)$$

where $\alpha_w = h/H$, $y = \beta z/H$, C_t is the transfer coefficient and P_s is the leaf shelter factor.

In the model physics we considered r_b as the total resistance, what implicitly includes an assumption that both forms free and forced convection equally contribute to convection over the whole unstable region.

The resistance to water vapour and heat flow from the soil surface to air space within the canopy is represented by an aerial resistance r_d, which is parameterized as

$$r_d = \int_{h_o}^{h}\frac{1}{K_m}\mathrm{d}z = \frac{1}{k^2 u_H}\left[\frac{\sinh(\beta)}{\sinh(\alpha_w \beta)}\right]^{1/2}\ln^2\left(\frac{h}{h_o}\right) \quad (34)$$

where h_o is the effective roughness length. The aerodynamic resistances were modified taking into account the effect of non-neutrality (Businger et al., 1971).

In the LAPS scheme stomatal resistance, r_s, depends both upon the atmospheric factors and water stress. This dependence is given in the form:

$$r_s = r_{smin}\Phi_1\Phi_2^{-1}\Phi_3^{-1}\Phi_4^{-1} \quad (35)$$

where r_{smin} is the minimum stomatal resistance.

The factor Φ_1 gives the dependence on the solar radiation. We parameterized it using expression suggested by Dickinson (1984):

$$\Phi_1 = (1 + f)(f + r_{smin}/r_{smax})^{-1} \quad (36)$$

where

$$f = 1.1\,R_o^s/(R_{gl}\,\mathrm{LAI}) \quad (37)$$

where LAI is the leaf area index, R_o^s the incoming short wave radiation and R_{gl} the limit value of 30 W m^{-2} for a forest and 100 W m^{-2} for crops. The value of 5000 s m^{-1} for r_{smax} was used. The factors Φ_2, Φ_3 and Φ_4 are limited to a range from 0 to 1 and their product is usually called the adjustment factor.

The factor Φ_2 takes into account the effect of the water stress on the stomatal resistance and it is parameterized in the following way:

$$\Phi_2 = \begin{cases} 1 & w_a > w_{fc} \\ 1 - \left(\frac{w_{wil}}{w_a}\right)^{1.5} & w_{wil} \le w_a \le w_{fc} \\ 0 & w_a < w_{wil} \end{cases} \quad (38)$$

where w_a is the mean volumetric water content in the first and second soil layer, w_{wil} the volumetric soil moisture content at wilting point and w_{fc} volumetric soil moisture content at field capacity.

The factor Φ_3 gives the dependence of stomatal resistance on the air temperature. According to Dickinson et al. (1986) this factor can be written in the form:

$$\Phi_3 = 1.0 - 0.0016(298 - T_r)^2 \quad (39)$$

where T_r is the air temperature at the reference level.

The factor Φ_4 represents the effect of atmospheric water vapor pressure deficit. It is parameterized following Jarvis (1976) who suggested the following form

$$\Phi_4 = 1 - \eta[e_*(T_f) - e_r] \quad (40)$$

where $e_*(T_f)$ is the saturation water vapor pressure for canopy temperature T_f, e_r the water vapor pressure at some reference level and η the species-dependent empirical parameter that is equal to 0.025 h Pa^{-1}.

The bulk stomatal resistance, r_c, represents the effective stomatal resistance per unit ground surface area and it is given by

$$r_c = r_s/\mathrm{LAI} \quad (41)$$

The leaf water potential Ψ_l describing the water transfer pathway from root zone to leaf is calculated following Van der Honert (1948),

$$\psi_l = \psi_r - z_t - E_{tf}(r_{plant} + r_{soil})/\rho_w \quad (42)$$

where Ψ_r is the soil moisture potential in the root zone, z_t the height of the transpiration source (equal to canopy source height, h_a), E_{tf} the transpiration rate, r_{plant} the plant resistance imposed by the plant vascular system prescribed as a variable, r_{soil} the resistance of the soil and root system. The canopy source height, h_a, is defined as a center of action of bulk aerodynamic resistance within the canopy. An estimation for h_a is suggested by Mihailović and Rajković (1993) in the following form:

$$h_a = H\{1 + 2/\beta \ln[0.5[1 + \exp(\beta(h/H - 1))]]\} \quad (43)$$

The soil water potential in the root zone, Ψ_r, is parameterized as an average term obtained by summing the weighted soil water potentials of the soil layers from the surface to the rooting depth, z_d,

$$\psi_r = \sum_{o}^{z_d} (\psi_i D_i)/z_d \quad (44)$$

where Ψ_i is the soil water potential of the ith soil layer and D_i the depth of the ith soil layer. The soil water potential, Ψ_i, is parameterized as it is usually done, after Clapp and Hornberger (1978),

$$\psi_i = \psi_s(w_i/w_s)^{-B} \quad (45)$$

where Ψ_s is the soil water potential at saturation, w_i and w_s are the volumetric soil moisture content of the ith soil layer and its value at saturation and B the soil type constant.

The depth-averaged resistance r_{soil} to water flow from soil to roots, is parameterized according to Federer (1979),

$$r_{soil} = (R/D_d + \alpha_j/K_r)/z_d \quad (46)$$

where

$$\alpha_j = \{V_r - 3 - 2\ln[V_r/(1 - V_r)]\}/(8\pi D_d) \quad (47)$$

and where R is the resistance per unit root length, D_d the root density, V_r the volume of root per unit volume of soil and K_r the mean soil hydraulic conductivity in the root zone expressed as function of Ψ_r:

$$K_r = K_s(\psi_s/\psi_r)^{(2B+3)/B} \quad (48)$$

where K_s is the saturated hydraulic conductivity.

The bare soil surface resistance, r_1, governs moisture flux from the top soil layer into the atmosphere. This surface resistance is parameterized following the empirical expression given by Sun (1982),

$$r_1 = p_1 + p_2(w_1/w_s)^{-p_3} \quad (49)$$

where p_1, p_2 and p_3 are empirical constants obtained from the data, equal to 30, 3.5 and 2.3, respectively (Sellers et al., 1989).

6. Hydrology parameterization

Moving from top to bottom of the soil water column the LAPS has the three layers (Fig. 1). The governing equations for the three volumetric soil moisture content are given by Eq. (5)–(7). The terms E_g, $E_{tf,1}$ and $E_{tf,2}$ in these equations are already defined by Eq. (11) and (15) thus, in this section we will define rest of terms in them.

The precipitation P_1 that infiltrates into the top soil layer is given by

$$P_1 = \begin{cases} \min(P_o, K_s) & w_1 < w_s \\ 0 & w_1 = w_s \end{cases} \tag{50}$$

where K_s is the saturated hydraulic conductivity and P_o the effective precipitation rate on the soil surface given by

$$P_0 = P - (P_f - D_f) \tag{51}$$

The rate of interception (inflow) for the canopy, P_f, is given by

$$P_f = P(1 - e^{-\alpha_{if}})\sigma_f \tag{52}$$

where P is the precipitation rate above the canopy, α_{if} a constant depending on the leaf area index. It is assumed that the interception of the rainfall can be considered via the expression describing the exponential attenuation (Sellers et al., 1986). The rate of drainage of water stored on the vegetation (outflow) for the canopy, D_f, is given by

$$D_f = \begin{cases} 0 & w_f < w_{max} \\ P_f & w_f = w_{max} \end{cases} \tag{53}$$

The transfer of water between adjacent layers $F_{i,i+1}$, is given by

$$F_{i,i+1} = K_{ef}[2(\psi_i = \psi_{i+1})/(D_i + D_{i+1}) + 1)] \tag{54}$$

where Ψ_i is the soil moisture potential of the ith layer, obtained by Eq. (45) and K_{ef} the effective hydraulic conductivity between soil layers given by

$$K_{ef} = (D_i K_i + D_{i+1} K_{i+1})/(D_i + D_{i+1}) \tag{55}$$

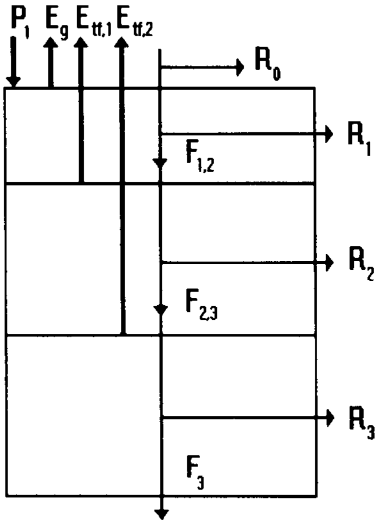

Fig. 2. Representation of runoff and drainage for LAPS scheme.

where K_i is the hydraulic conductivity of the ith soil layer determined by the empirical formula

$$K_i = K_{si}(w_i/w_s)^{2B+3} \tag{56}$$

where K_{si} is the hydraulic conductivity at saturation of the ith soil layer.

The gravitational drainage from the bottom soil layer is defined as

$$F_3 = K_{si}(w_3/w_s)^{2B+3} \sin x \tag{57}$$

where x is the mean slope angle (Sellers et al., 1986; Abramopoulos et al., 1988).

The schematic diagram representing the drainage and runoff in the LAPS is shown in Fig. 2. The surface runoff R_o is computed as

$$R_o = P_1 - \min(P_1, K_s) \tag{58}$$

The subsurface runoff is calculated for each soil layer using the expressions

$$R_1 = F_{1,2} - \min(F_{1,2}, K_s) \tag{59}$$

$$R_2 = F_{2,3} - \min(F_{2,3}, K_s) \tag{60}$$

$$R_3 = F_3 - \min(F_3, K_s) \tag{61}$$

At the end of time step, Δt, the value Γ_i is calculated as

$$\Gamma_i = \frac{D_i}{\Delta t}\left[w_i^k + A_i \Delta t - w_{fc}\right] \tag{62}$$

where w_i^k is the volumetric soil moisture content at the beginning of k time step while A_i representing the terms on the right side of Eq. (5)–(7). If the condition $\Gamma_i > 0$ is satisfied then the Γ_i becomes runoff which is added to corresponding subsurface runoff R_i. Consequently, at the end of the time step, the calculated value of the volumetric soil moisture content w_i^{k+1} takes the value w_{fc}.

7. Summary and further plans

We have given a detailed description of a parameterization of land surface processes. In designing the scheme, we tried to find a compromise between an accurate description of the main physical processes and the restriction of the number of prescribed input parameters.

In this version the LAPS was evaluated using micrometeorological measurements over: maize, winter wheat and soya fields. The scheme accurately reproduced the observed values of the components of the surface energy balance with the parameterization which has been able to capture most of the main physical processes involved (Mihailović et al., 1993; Mihailović and Jeftić, 1994 and Mihailović and Ruml, 1996).

In further development of the LAPS scheme, more attention has to be devoted to two fundamental points: energy partitioning (i.e. the partitioning of available energy between surface sensible and latent heat fluxes in the surface budget equation) and water partitioning (i.e. the partitioning of precipitation between evaporation and runoff–drainage in water budget equation). It will include reconsideration of some formulations in current parameterization of evapotranspiration and hydrology using more specific tests.

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References

Abramopoulos, F., Rosenzweig, C. and Choudhury, B., 1988. Improved ground hydrology calculations for global climate models (GCMs): Soil water movement and evapotranspiration. J. Climate, 1: 921–941.

Businger, J.A., Wyngaard, J.C., Izumi, Y.I. and Bradley, E.F., 1971. Flux-profile relationship in the atmospheric surface layer. J. Atmos. Sci., 28: 181–189.

Clapp, R.B. and Hornberger, G.M., 1978. Empirical equations for some soil hydraulic properties. Water Resour. Res., 14(4): 601–604.

Deardorff, J.W., 1978. Efficient prediction of ground surface temperature and moisture with inclusion of a layer vegetation. J. Geophys. Res., 83: 1889–1903.

Dickinson, R.E., 1984. Modeling evapotranspiration for threedimensional global climate models. In: J.E. Hansen and T. Takahashi (Editors), Climate Processes and Climate Sensitivity. Am. Geophys. Union, Washington, DC, pp. 58–72.

Dickinson, R.E., Henderson-Sellers, A., Kennedy, P. and Wilson, M., 1986. Biosphere/Atmosphere Transfer Scheme for NCAR Community Climate Model. NCAR Tech. Note TN 30.

Federer, C.A., 1979. A soil–plant–atmosphere for transpiration and availability of soil water. Water Resour. Res., 15(3): 555–562.

Goudriaan, J., 1977. Crop Micrometeorology. A Simulation Study. Wageningen Center for Agric. Publ. Doc., 249 pp.

Henderson-Sellers, A., Yang, Z.L. and Dickinson, R.E., 1993. The project for intercomparison of land-surface parameterization schemes. Bull. Am. Meteorol. Soc., 74: 1335–1349.

Idso, S., Jackson, R., Kimball, B. and Nakagama, F., 1975. The dependence of bare soil albedo on soil water content. J. Appl. Meteorol., 14: 109–113.

Jarvis, P.G., 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. Philos. Trans. R. Soc., B273: 593–610.

Mihailović, D.T., 1990. Testing the Biosphere–Atmosphere Transfer scheme (BATS) using Penman and Long (1960) data: Preliminary results. Int. Rep. Dep. Meteorol. Wageningen Agric. Univ., 40 pp.

Mihailović, D.T., 1991. A model for prediction of the soil temperature and the soil moisture content in three layers. Z. Meteorol., 41: 29–33.

Mihailović, D.T. and Jeftić, M., 1994. An efficient but simple biophysical scheme UNICOS for use in different scale modelling. Environ. Soft., 9: 47–60.

Mihailović, D.T. and Rajković, B., 1993. Surface vegetation parametrization in atmospheric models: A numerical study. Z. Meteorol., 2: 239–243.

Mihailović, D.T. and Ruml, M., 1996. Design of land–air parameterization scheme (LAPS) for modelling boundary layer surface processes. Meteorol. Atmos. Phys., 58: 65–81.

Mihailović, D.T., Pielke, R.A., Rajković, B., Lee, T.J. and Jeftić, M., 1993. A resistance representation of schemes for evaporation from bare and partly plant-covered surfaces for use in atmospheric models. J. Appl. Meteorol., 32: 1038–1054.

Sellers, P.J., Mintz, Y., Sud, Y. and Dacher, X., 1986. A simple biosphere model (SiB) for use within general circulation model. J. Atmos. Sci., 43: 506–531.

Sellers, P.J., Shuttleworth, W.J., Dorman, J.L., Dalcher, A. and Roberts, J.M., 1989. Calibrating the simple biosphere model for Amazonian forest using field and remote sensing date. Part I: Average calibration with field data. J. Appl. Meteorol., 28: 727–759.

Shao, Y., Rama, A.D., Henderson-Sellers, A., Thornton, P., Liang, X., Chen, T.H., Ciret, C., Desborough, C., Balachova, O., Haxeltine, A. and Ducharne, A., 1994. Soil moisture simulation. A report of the RICE and PILPS Workshop. IGPO Publ. Ser., 14, 170 pp.

Sun, S.F., 1982. Moisture and heat transport in a soil layer forced by atmospheric conditions. M.S. Thesis. Dep. Civ. Eng. Univ. Conn., 72 pp.

Van der Honert, X., 1948. Water transport as a catenary process. Disc. Faraday Soc., 3: 146–153.

Zhang, D. and Anthes, R.A., 1982. A high-resolution model of the planetary boundary layer-sensitivity tests and comparisons with SESAME-79 data. J. Appl. Meteorol., 21: 1594–1609.