Computing energy budget within a crop canopy from Penmann's formulae

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The Lhomme's model (1988a), that extended Penmann's formulae to a multi-layer model, is redefined as a function of micrometeorological and physiological profiles of crop canopy. The sources and sinks of sensible and latent heat fluxes are assumed to lie on a fictitious plane called zero-displacement plane. Algorithms are given to compute sensible and latent heat flux densities. Performance of the algorithms is compared with that of earlier algorithms.

1. Introduction

For natural surfaces, the partitioning of available energy (Rn - S) into sensible heat flux (H) and latent heat flux (λE) is accounted by the well-known Penmann's equations (Penmann 1948, 1953):

$$H = \frac{\Delta(Rn - S) - \rho c_p Da/r_a}{\Delta + \gamma(1 + r_s/r_a)}, \quad (1)$$

$$\lambda E = \frac{\Delta(Rn - S) + \rho c_p Da/r_a}{\Delta + \gamma(1 + r_s/r_a)}, \quad (2)$$

where Rn is the net radiation, S is the soil heat flux, Da is the vapour deficit of air at a reference height, γ is the psychrometric constant, Δ is the slope of saturated vapour pressure curve at the air temperature, c_p the specific heat of air at constant pressure, and ρ the mean density of air. r_a is the aerodynamic resistance calculated between the surface level and the reference height and r_s being the surface resistance for water vapour transfer. In practice, there are two types of models: single layer and multi-layer models. The single layer model describes the convective transfers from a surface comprising of vegetation and underlying surface as a lumped system. Such a surface is treated as a single source. Monteith (1981) applied this approach to a vegetation stand on the assumption that the vegetation stand acts as a single equivalent surface absorbing radiative energy and transfering sensible and latent heat fluxes to the air. Deardorff (1978) developed single layer parameterization of vegetation that involved the solution of energy budget equation.

In multi-layer models (Waggoner and Reifsnyder 1968; Shuttleworth 1976; Chen 1984; Meyers and Paw 1986; and Naot and Mahrer 1989), vertical transport of sensible and latent heat is described by considering a continuous or discrete set of horizontal planes, each one exchanging heat and vapour with the air. These models include parameterization of stomatal response to the environmental conditions, along with some models for heat and water fluxes into and out of soil layer.

Lhomme (1988a) presented a model based on electrical analogue that simulates energy exchange between vegetation and atmosphere. In his model, Lhomme assumed the sources and sinks of sensible and latent heat fluxes to be uniformally distributed throughout the height of canopy rather than concentrated at a level inside the canopy.

Agricultural crops mostly consist of a large number of roughness elements with irregular shapes being distributed more or less uniformly over some area. The aerodynamic roughness parameter (z_0) and displacement height (d) are the two important elements of the surface properties that control the surface–atmosphere interactions. Usually, z_0 is interpreted as a length scale that characterises the efficiency for removing momentum from the flow and d is interpreted as an effective level of underlying surface on which source and sink are supposed to lie.

Keywords. Latent heat flux; sensible heat flux; net radiation; aerodynamical resistance; boundary layer resistance; stomatal resistance.

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The purpose of this paper is to redefine Lhomme's model (1988a) in the frame of roughness length parameter (z_0) and the zero-displacement height (d). To handle the model more efficiently, the micrometeorological and physiological profiles of the crop have been introduced as initial conditions to arrive at final solutions. The solutions in compact form provide simultaneous calculation algorithms to calculate sensible and latent heat flux densities. The methods of numerical simulation of Lhomme (1988b) have been adopted to operate the model for a standard canopy like a maize crop. The latent heat fluxes computed from reformulated model as functions of stomatal resistance profile and different values of soil surface resistance are presented and compared with those computed by Lhomme (1988b).

2. Basic equations in multi-layer model

The crop canopy, assumed to be horizontally homogeneous, is divided into several parallel thin layers. Subscript i refers to the layer number counted from 1 to n from top of canopy to soil surface. LAI_i is the leaf area index of layer i per unit ground surface area and $T_{L,i}$ is the mean temperature of the leaves in the layer i. $e_s(T_{L,i})$ is the vapour pressure inside the stomatal cavity that is assumed to be saturated at leaves temperature $T_{L,i}$ in layer i. $T_{a,i}$ and $e_{a,i}$ are the mean temperature and vapour pressure of air in layer i.

The Lhomme's model (1988a) is based on electrical analogue in which sensible and latent heat fluxes replace the current, and corresponding potentials are, respectively, $\rho c_p T$ for sensible heat and $(\rho c_p/\gamma)e$ for latent heat. In the diffusion process between leaves and air, the latent heat experiences two kinds of resistance: the stomatal resistance rs_i, and boundary layer resistance rb_i while the sensible heat flux experiences only boundary layer resistance, assumed to be the same for both transfers. Assuming the atmosphere to be neutral, the elementary fluxes in each layer can be written as:

$$\delta H_i = \rho c_p(T_{L,i} - T_{a,i})/re_{c,i}, \tag{3}$$

$$\delta\lambda E_i = (\rho c_p/\gamma)(e_{s,i}(T_{L,i}) - e_{a,i})/re_{\nu,i} \tag{4}$$

with

$$re_{c,i} = rb_i/2LAI_i, \tag{5}$$

$$re_{\nu,i} = (rs_i + rb_i)/2LAI_i. \tag{6}$$

Vertical fluxes denoted by H_i and λE_i experience a diffusive resistance ra_i while crossing the layer i. They can be written as:

$$H_i = \frac{\rho c_p(T_{L,i} - T_{a,i})}{ra_{i-1}}, \tag{7}$$

$$\lambda E = (\rho c_p/\gamma)\left[\frac{e_{a,i}(T_{L,i}) - e_{a,i}}{ra_{i-1}}\right], \tag{8}$$

where the diffusive resistance ra_i is related to the eddies diffusivity $K(z)$ within the canopy by the relation:

$$ra_i = \int_{z_i}^{z_{i-1}} \frac{dz}{K(z)}. \tag{9}$$

3. Micrometeorological and physiological profiles

In this section, the micrometeorological and physiological profiles of the canopy are stated and will be used in simultaneity with the basic equations mentioned above.

3.1 *Net radiation*

The extinction of net radiation within the canopy can be described by Beer's law:

$$Rn = Rn(h)\exp\big[-\alpha_r LAI(z/h)\big], \tag{10}$$

where h is the height of canopy from the soil surface. The extinction coefficient α_r depends upon the structure of canopy. α_r varies from 0.45 to 0.65 for maize and rice crops (Monteith 1976).

The soil flux S is generally taken as a fraction of net radiation reaching the ground and can be expressed as:

$$S = \mu Rn \tag{11}$$

with $\mu = 0.1$ (Campbell 1977).

3.2 *Aerodynamic resistance*

In the neutral condition, assuming the roughness lengths for heat and momentum to be equal, the aerodynamic resistance ra_0 above the top of canopy (reference height) can be expressed as:

$$ra_0 = \frac{\ln\big[(z_r - d)/(h-d)\big]\ln\big[(z_r - d)/z_0\big]}{k(u)^2}, \tag{12}$$

where (u) is the wind speed measured at reference height z_r. k is the von Karman constant (0.41). The analysis of wind records obtained in near neutral condition showed that means values of d and z_0 for maize and rice crops increase with increasing stand height. For rice and maize crops this dependence can be approximated by (Monteith 1976):

$$d = 1.04h^{0.88} \text{ and } z_0 = 0.062h^{1.08}. \tag{13}$$

3.3 *Boundary layer and stomatal resistances*

The boundary layer resistance of the leaves rb_i in the layer i can be related to local wind speed u_i by the relation (Perrier 1976):

$$rb_i(z) = rb_0 u_i^a(z), \tag{14}$$

where $rb_n = 50$ (for soil surface) and $a = -0.5$.

A simple parameterization as a function of global radiation can be used to describe stomatal resistance profile:

$$rs = k_0/Rg(z), \tag{15}$$

where $Rg(z)$ is the short-wave global radiation given by

$$Rg(z) = Rg(h)\exp\big[-\alpha_r LAI(z/h)\big]. \tag{16}$$

The extinction coefficient α_r is the same for both; the net radiation and global radiation. k_0 is a parameter which varies as a function of water status. For a completely wet crop, k_0 is zero but equal to 9×10^5 for an important water stress.

In view of the above relations, the quantities $re_{c,i}$ and $re_{v,i}$ appearing in equations (3), (4), (5) and (6) can be written as:

$$re_{c,i} = rb_i u_i^a(z)/2LAI_i, \tag{17}$$

$$re_{v,i} = [k_0\exp(\alpha_r LAI_i(z_i/h))/Rg_i + rb_i u_i^a(z)]/2LAI_i. \tag{18}$$

3.4 *Wind speed and eddies diffusivity profiles*

Many workers have used K-theory (flux gradient theory) to simulate exchange between vegetation canopy and the atmosphere. For a neutral atmosphere, the wind speed and eddy diffusivity can be assumed to decrease exponentially within the canopy (Choudhary and Monteith 1988; Shuttleworth and Gurney 1990):

$$u(z) = u(h)\exp[-\alpha_w(z/h)], \tag{19}$$

$$K(z) = K(h)\exp[-\alpha_w(z/h)]. \tag{20}$$

The value of α_w for maize crops ranges from 2.5 to 3.0 (Monteith 1976). From K-theory, eddy diffusivity $K(h)$ and wind speed $u(h)$ at the canopy level are related as:

$$K(h) = K(0)u(h), \tag{21}$$

where $K(0)$ represents eddy diffusivity at the reference height z_r given by

$$K(0) = k^2(h-d)/\ln[(h-d)/z_0]. \tag{22}$$

The wind speed at canopy level $u(h)$ can be calculated from wind speed (u) measured at the reference height z_r by the following relation:

$$u(h) = [\ln\{(h-d)/z_0\}/\ln\{(z_r-d)/z_0\}](u). \tag{23}$$

Using equations (19)–(23), integration of (9) yields the following expression for aerodynamic resistance ra_i within the canopy:

$$ra_i = h[1-\exp(\alpha_w\Delta z/h)]\exp(\alpha_w z_{i-1}/h)/[K(0)\alpha_w u(h)], \tag{24}$$

where $\Delta z = z_{i-}z_{i-1}$.

4. Lhomme's model

The total fluxes at the top of the canopy can be expressed as the algebraic sum of the contributions of each layer:

$$H_0 = \sum\delta H_i,\ \lambda E_0 = \sum\delta\lambda E_i,\ Rn_0 = \sum\delta Rn_i, \tag{25}$$

followed by conservation equations:

$$H_i = H_{i+1} + \delta H_i, \lambda E_i = \lambda E_{i+1} + \delta\lambda E_i, \quad \text{and} \quad Rn_i = Rn_{i+1} + \delta Rn_i. \tag{26}$$

From equation (10)

$$\delta Rn_i = Rn_i - Rn_{i+1} = Rn_i\big[1-\exp(-\alpha_r LAI_i z_i/h)\big]. \tag{27}$$

The net radiation absorbed in each layer balances convective fluxes of sensible and latent heat:

$$\delta Rn_i = \delta H_i + \delta\lambda E_i. \tag{28}$$

This equation is still valid for layer n (soil surface) if δRn_i is replaced by $\delta Rn_i - S$. Thus the equation (28) can be summed up from 1 to n to give:

$$\sum_{i=1}^{n}\delta Rn_i - S = H_0 + \lambda E_0. \tag{29}$$

The equations (11) and (29) yield:

$$\sum_{i=1}^{n}\delta Rn_i - S = (1-\mu)\times\sum_{i=1}^{n} Rn_i\big[1-\exp(-\alpha_r LAI_i z_i/h)\big]. \tag{30}$$

Now, without going into details about the derivations of Lhomme's model (1988a), the final expressions of Lhomme's model for sensible and latent heat fluxes are written as functions of quantities enlisted above.

Linearising the saturated vapour pressure versus temperature curve between $T_{L,i}$ and $T_{a,i}$ by the slope Δ of the curve determined at air temperature $T_{a,i}$ at the reference height, we get

$$\Delta = \big[e_s(T_{L,i}) - e_s(T_{a,i})\big]/(T_{L,i} - T_{a,i}). \tag{31}$$

The vapour pressure deficit in each layer is written as:

$$Da_i = e_s(T_{a,i}) - e_{a,i}. \quad (32)$$

Now, the equation (4) can be written as:

$$\delta\lambda E_i = (\frac{\rho c_p}{\gamma})\big[\Delta(T_{L,i} - T_{a,i}) + Da_i\big]/re_{\nu,i}. \quad (33)$$

The equations (8), (27), and (33) together give:

$$T_{L,i} - T_{a,i} = d_i\delta Rn_i/\rho c_p - d_i Da_i/\gamma re_{\nu,i}, \quad (34)$$

where

$$d_i = \frac{re_{\nu,i}re_{c,i}}{re_{\nu,i} + (\rho c_p/\gamma)re_{c,i}}. \quad (35)$$

Lhomme (1988a) gave the following expressions for H_0 and λE_0 respectively:

$$H_0 = \sum_{i=1}^{n} d_i\delta Rn_i/re_{c,i} - (\rho c_p/\gamma) \sum_{i=1}^{n} d_i Da_i/re_{\nu,i}re_{c,i}, \quad (36)$$

$$\lambda E_0 = (\Delta/\gamma)\sum_{i=1}^{n} d_i\delta Rn_i/re_{\nu,i} + (\rho c_p/\gamma) \sum_{i=1}^{n} d_i Da_i/re_{\nu,i}re_{c,i} \quad (37)$$

with Da_i in recurrent form

$$Da_i = \alpha_i Da_1 + \beta_i\Delta J_0 ra_1/\rho c_p + \sum_{i=1}^{n}\varepsilon_i^j\delta Rn_i/\rho c_p. \quad (38)$$

The coefficients α_i, β_i and ε_i^j can be evaluated from the following relations:

$$\begin{aligned}\alpha_{i+1} &= a_i\alpha_i + b_i\alpha_{i-1},\\ \beta_{i+1} &= a_i\beta_i + b_i\beta_{i-1},\\ \varepsilon_{i-j}^{j<i-1} &= a_i\varepsilon_i^j + b_i\varepsilon_{i-1}^j,\\ \varepsilon_{i+1}^{i-1} &= a_i\varepsilon_i^{i-1} = a_i c_{i-1},\\ \varepsilon_{i+1}^{i} &= c_i\end{aligned} \quad (39)$$

with first coefficients defined as:

$$\alpha_1 = 1, \beta_1 = 0, \alpha_2 = a_1, \beta_2 = 1, \varepsilon_2^1 = c_1, \quad (40)$$

where

$$\begin{aligned}b_i &= -\frac{ra_i}{ra_{i-1}},\\ a_i &= 1 - b_i - c_{\nu,i} + (\Delta/\gamma)(c_{\nu,i} - c_{c,i})d_i/re_{\nu,i},\\ c_{c,i} &= -\frac{ra_i}{re_{c,i}},\\ c_{\nu,i} &= -\frac{ra_i}{re_{\nu,i}},\\ c_i &= \Delta(c_{c,i} - c_{\nu,i}),\\ J_0 &= H_0 - (\gamma/\Delta)\lambda E_0.\end{aligned} \quad (41)$$

Lhomme (1988a) further simplified the expressions using Monteith equations (1981) for the total flux density at the top of the canopy:

$$\lambda E_0 = \big[\Delta(Rn - S) + \rho c_p(Da_0 - Da_1)/ra_0\big]/(\Delta + \gamma), \quad (42)$$

where Da_0 is the saturation deficit of air at reference height above the canopy and ra_0 is the aerodynamic resistance between the reference height and canopy level. ra_0 can be determined from the equation (12).

To keep consistency with equation (42), Lhomme (1988a) expressed Da_1 as a function of Da_0 such as:

$$Da_1 = Da_0 + \alpha_1 ra_0\Delta J_0/\rho c_p. \quad (43)$$

Inserting Da_1 in relation (38) and then substituting Da_i in relations (36), (37) and again making use of (29) and (30), the final expressions for redefined form of Lhomme's model (1988a) are obtained as:

$$H_0 = \big[\gamma(1 + A + B)(1-\mu)\sum_{i=1}^{n} Rn_i\{1 - \exp(-\alpha_r LAI_i z_i/h)\} - \sum_{i=1}^{n} E_i Rn_i\{1 - \exp(-\alpha_r LAI_i z_i/h)\} - \rho c_p A Da_0/ra_0\big]/\{\gamma + (\Delta+\gamma)(A+B)\}, \quad (44)$$

$$\lambda E_0 = \big[\gamma(A+B)(1-\mu)\sum_{i=1}^{n} Rn_i\big\{1 - \exp(-\alpha_r LAI_i z_i/h)\big\} + \sum_{i=1}^{n} E_i Rn_i\big\{1 - \exp(-\alpha_r LAI_i z_i/h)\big\} + \rho c_p A Da_0/ra_0\big]/\{\gamma + (\Delta+\gamma)(A+B)\}, \quad (45)$$

Table 1. *For a wet soil surface ($rs_n = 0$), the computed $\lambda E_0 (Wm^{-2})$ are shown as functions of stomatal resistance profile specified by the value of k_0.λE_0^* is denoted for Lhomme's model.*

$k_0(10^5)$	0	1	2	3	4	5	6	7	8	9
λE_0	586	422	339	289	256	231	211	195	181	171
λE_0^*	564	409	330	281	249	226	208	194	183	174

Table 2. *For dry soil surface, the same variations as in table 1. The soil surface resistance is taken equal to the stomatal resistance of the last vegetation layer.*

$k_0(10^5)$	0	1	2	3	4	5	6	7	8	9
λE_0	586	402	307	248	206	179	154	139	123	111
λE_0^*	564	391	300	243	204	176	155	138	125	114

where

$$\varepsilon_i^i = \Delta re_{c,i},$$
$$E_i = \sum_{j=1}^{n} d_j \varepsilon_j^i / re_{c,j} re_{\nu,j},$$
$$A = ra_0 \sum_{i=1}^{n} d_i \alpha_i / re_{c,i} re_{\nu,i}, \quad (46)$$
$$B = ra_1 \sum_{i=1}^{n} d_i \beta_i / re_{c,i} re_{\nu,i}.$$

5. Numerical simulation

All elementary resistances such as stomatal, and boundary layer, are supposed to be known as also the net radiation at canopy level. From the measured height of the canopy, zero-displacement height (d) and roughness length (z_0) can be calculated (equation 13). Thereafter, the wind speed (u) measured at reference height level (z_r) can be used to determine the wind speed $u(h)$ at the canopy level (h) from equation (23). The eddies diffusivity $K(0)$ at reference level z_r calculated from equation (22) will yield eddies diffusivity $K(h)$ at canopy level from equation (21). Similarly, the aerodynamic resistance ra_0 at the reference level can be determined from equation (12). The quantities $u(h)$, $K(h)$ and $K(0)$ already calculated can be inserted in equation (24) to get the aerodynamic resistance ra_1 at the canopy level.

In this way, all quantities computed at the canopy level will be treated as initial values for further computations down to soil level by assigning $i = 1$. Some computed results are presented for microclimate of a maize crop and compared with those presented by Lhomme (1988b). The physiological characteristics of maize crop (Lhomme 1988b) are as follows:

Canopy height (h)	: 1.5m,
Number of layers in vegetation (n)	: 5,
Layer thickness (Δz)	: 0.3m per layer,
Leaf area profile (LAI)	: constant (0.6 per layer)
Extinction coefficient (α)	: 0.55,

$\alpha_w = 2.75$,
$Rn = 60\%$ of Rg.

The climatic characteristics at reference height (z_r) of 3m are:

Air temperature ($T_{a,0}$)	: 25°C,
Vapour pressure ($e_{a,0}$)	: 2000Pa,
Wind speed (u)	: 3ms^{-1},
Global radiation (Rg)	: 800Wm^{-2}.

Using the input values mentioned above, computations for latent heat fluxes (λE_0) have been carried out and the results so found are presented in the tables 1–3. Corresponding latent heat fluxes (denoted by λE_0^*) calculated by Lhomme (1988b) are also shown in the tables. In table 1, the soil surface is considered to be wet ($rs_n = 0$). In table 2, the soil surface is considered to be dry so that rs_n is set equal to the stomatal resistance of the last vegetation layer. In table 3, for a given stomatal profile corresponding to $k_0 = 4 \times 10^5$, latent heat fluxes are shown as functions of soil surface resistance rs_n.

From tables 1 and 2, it is seen that the redefined model yields the value of λE_0 greater than that of λE_0^* given by Lhomme's model (1988b) but the increase is very much pronounced when the crop canopy is completely wet ($k_0 = 0$). As the stomatal resistance (rs_i) of the canopy increases, λE_0 gets gradually closer to λE_0^* and finally becomes almost equal at highest water stress ($k_0 = 9 \times 10^5$). Similar characteristics are seen in table 2 too. In table 3, the trend looks similar. Initially, λE_0 decreases as the soil surface resistance (rs_n) increases but later

Table 3. λE_0 *and* λE_0^* *are shown as functions of soil resistance* (sm^{-1}) *for a given stomatal profile corresponding to* $k_0 = 4 \times 10^5$. *The stomatal resistance of the last vegetation layer is* $2700 sm^{-1}$.

rs_n	0	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	7000
λE_0	256	229	214	208	206	204	201	199	198.6	198	197.7	197.2	196.4	196
λE_0^*	249	225	216	210	207	205	203	202	201	200			199	198

becomes almost constant as the soil surface resistance goes on increasing.

6. Conclusion

Lhomme (1988a) extended mathematically the Penmann's formulae to multi-layer model with expressions partitioning available radiative energy into sensible and latent heat fluxes. Lhomme assumed the sources and sinks to be distributed uniformly throughout the height of the canopy. Further, the model does not seem to be very elaborate in dealing with the micrometeorological and physiological profiles of the crop explicitly.

In this paper, Lhomme's model (1988a) is redefined with the assumption that the sources and sinks lie on a fictitious plane so called zero-displacement plane. In the frame of zero-displacement height and roughness length, expressions for sensible and latent heat fluxes have been obtained as functions of micrometeorological and physiological profiles of crop. Lhomme (1988b) presented some computed values of latent heat flux for maize crop stand. Using the same input values, latent heat flux has been calculated from redefined model for maize crop. On comparing the results, it is found that the redefined model yields the flux greater than the Lhomme's model (1988b) when the crop is completely wet. On the other hand, the two models are found to be nearly identical at a large value of stomatal resistance of the canopy.

The advantage with the redefined model is that the input parameters are systematically defined, thus giving their initial values at the top of the canopy or at a reference height. There is no need to compute separately the micrometeorological and physiological parameters as in the case of the Lhomme's model. In this way, the redefined model offers simplified calculation algorithms.

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