A MICROMETEOROLOGICAL MODEL TO SIMULATE LEAF WETNESS DURATION IN AN HOMOGENEOUS PLANT CANOPY AFTER RAIN OR DEW DEPOSIT

(with special emphasis on banana and plantain canopies)

Jean-Paul LHOMME*

Micrometeorologist,
CATIE, 7170 Turrialba, Costa Rica

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I. INTRODUCTION

Leaf surface wetness duration is an important aspect of plant epidemiology and protection because many pathogens need a film or droplets of free water over the leaf tissue for the spores to germinate and infect the host. It is specially the case of Black Sigatoka which is an important disease of plantain and banana in Central America. This disease is due to a fungus (Mycosphaerella fijiensis) and is directly related to leaf wetness persistence.

The model presented here constitutes a mechanistic simulation of the microclimate of a plant canopy aiming at predicting the persistence of free water on the leaves after rain or dew deposit. The main issue in this type of modelling is to calculate the evaporation rate of a partially wet canopy where evaporation takes place at one and the same time from drops on the leaves and from sub-stomatal cavities through the stomata. Several models describing the evaporation of an homogeneous plant canopy in partially wet conditions have been published (Thomson, 1981; Wronski, 1984; Butler, 1986; Huber, 1988). All these models use similar basic equations. They essentially differ by the approach, continuous or discrete, used to combine the basic equations and the way these equations are solved. In the continuous approach, differential equations are derived and, in the absence of analytical solutions, they are solved numerically. In the discrete approach, linear equations are obtained and solved either by means of matrix methods (Furnival et al., 1975) or by an iterative process (Chen, 1984).

Our model uses a discrete approach based on a division of the canopy into several parallel layers or strata, each characterised by a specific leaf area and a given foliage inclination. To simplify the problem we have retained only two types of leaf inclination distribution, vertical and horizontal. The first one corresponds to an erectophile canopy: vertical or nearly vertical leaves are predominant. The second one corresponds to a planophile canopy: horizontal or nearly horizontal leaves are predominant. In a banana or plantain canopy the upper part of the canopy is generally erctophile and the lower part planophile (Fig.1). In this document only the theoretical part of the modelling is presented. We show how the mathematical procedure to solve the basic equations of multi-layer models in partially wet conditions can be simplified. We demonstrate also that it is possible to derive explicit expressions of total fluxes of sensible and latent heat, of the same type as those given by Lhomme (1988) for a dry canopy, and very similar in form to the familiar Penman's formulae (Penman, 1948). Field tests of the performance of the model will be given in further documents.

Fig.1- Example of plantain canopy

II.PHYSICAL EQUATIONS

1.Basic equations of multi-layer models

The approach used to describe the energy transfers within the canopy and the vertical profile of evaporation is the classical multi-layer approach originally devised by Waggoner and Reifsnyder (1968).

The plant canopy, assumed to be horizontally homogeneous, is conceived as divided into n parallel layers, each specified by a partial leaf area index denoted by δLAI_i ($1<i<n$). Horizontal flux divergence is assumed to be negligible and the model is constructed in the vertical direction alone.

Air within layer i is specified by its mean temperature $T_{a,i}$ and its mean water vapour pressure $e_{a,i}$. The water vapour pressure $e_{L,i}$ inside the substomatal cavities, origin of water vapour transfer, is assumed to be saturated at the temperature of the leaves. If $T_{L,i}$ specifies the mean temperature of the leaves within layer i and $e_s(T)$ the saturated vapour pressure at temperature T, we shall write:

$$e_{L,i}=e_s(T_{L,i}) \quad . \qquad (A.1)$$

The whole stand is depicted as a circuit transmitting sensible and latent heat (Fig.2), the corresponding driving potentials being respectively $\rho c_p T$ and $\rho c_p/\tau$. ρ is the density of air , c_p is the specific heat of air at constant pressure and τ is the psychrometric constant.

The net radiation absorbed in each vegetation layer per unit surface of soil δRn_i balances elementary convective fluxes of sensible and latent heat δC_i and $\delta\lambda E_i$:

$$\delta Rn_i=\delta C_i+\delta\lambda E_i \quad . \qquad (A.2)$$

This equation is still valid for layer n (soil surface) if δRn_n is replaced by δRn_n-S, S being the soil heat flux.

The convective fluxes of sensible and latent heat emanating from each layer can be written respectively as:

$$\delta C_i=\rho c_p ge_{c,i}(T_{L,i}-T_{a,i}) \quad , \qquad (A.3)$$

$$\delta\lambda E_i=(\rho c_p/\tau)ge_{v,i}(e_s(T_{L,i})-e_{a,i}) \quad , \qquad (A.4)$$

$ge_{c,i}$ and $ge_{v,i}$ are the equivalent conductances for sensible and latent heat. They are directly related to the partial leaf area index δLAI_i and the specific conductances experienced by both fluxes. If $gs_{u,i}$ and $gs_{l,i}$ specifie

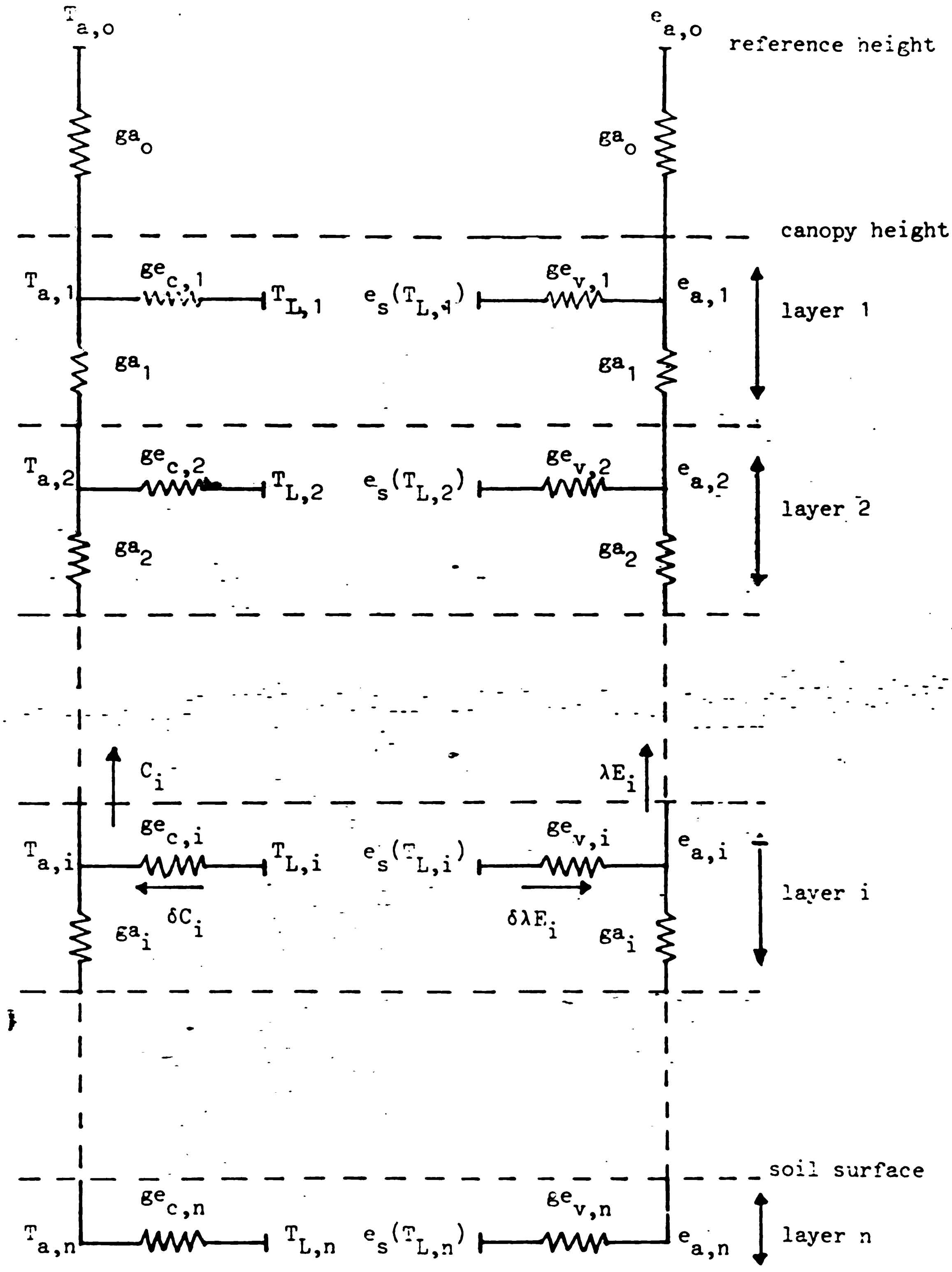

Fig.2 - Electrical analogue of exchange processes within the crop canopy

respectively the stomatal conductance of the upper side and lower side of the leaves in layer i, and if gb_i is the boundary-layer conductance of the leaves assumed to be the same for sensible heat and water-vapour transfers and for both side of the leaves, we shall write:

$$ge_{c,i}=2\delta LAI_i gb_i \quad , \qquad (A.5)$$

$$ge_{v,i}=[(1/gs_{u,i}+1/g_{b,i})^{-1}+(1/gs_{l,i}+1/gb_i)^{-1}]\cdot\delta LAI_i \quad . \qquad (A.6)$$

Equations (A.3) and (A.4) are still valid to describe the transfers at the ground surface provided $ge_{c,n}$ and $ge_{v,n}$ are calculated by means of the following equations:

$$ge_{c,n}=gb_n \quad , \qquad (A.7)$$

$$ge_{v,n}=[gs_n gb_n/(gs_n+gb_n)] \quad , \qquad (A.8)$$

where gb_n is the boundary-layer conductance of the soil surface and gs_n is a surface conductance for water vapour defined in the same way as for leaves.

The vertical transfer of sensible and latent heat in the air within the canopy is proportional to the vertical difference in the corresponding entity, temperature or humidity. The proportionality factor ga, called diffusive conductance, is assumed to be the same for both transfers and is calculated as the reciprocal of the integral of the reciprocal of eddy diffusivity K through the path considered (here the height of the stratum):

$$ga_i=1/\int_{z_i}^{z_{i-1}} (1/K(z))dz \quad . \qquad (A.9)$$

Within the canopy the flux-gradient relationship has been questioned (Legg and Monteith, 1975) and must be handled with care. But it seems it plays a secondary role in the partitioning of energy which determines the evaporation rate from the leaves (Butler, 1986).

According to the general scheme presented in Figure 2 the vertical fluxes leaving layer i and crossing layer i-1 upwards are written as:

$$C_i=\rho c_p ga_{i-1}(T_{a,i}-T_{a,i-1}) \quad , \qquad (A.10)$$

$$\lambda E_i=(\rho c_p/\tau)ga_{i-1}(e_{a,i}-e_{a,i-1}) \quad . \qquad (A.11)$$

ga_{i-1} can be calculated approximately as:

$$ga_{i-1} \approx K_{i-1}/\delta z_{i-1} \quad , \qquad (A.12)$$

where K_{i-1} is the mean diffusivity for the given layer i-1 and δz_{i-1} the layer thickness.

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

$$C_\emptyset = \sum_{i=1}^{n} \delta C_i \quad \text{and} \quad \lambda E_\emptyset = \sum_{i=1}^{n} \delta\lambda E_i \quad . \qquad (A.13)$$

2.Basic equations in partially wet conditions

a)General considerations

In partially wet conditions the basic equations described above have to be modified to account for free water deposited on leaves. We shall distinguish two types of canopy corresponding to two types of leaf angle distribution: erectophile and planophile. In erectophile canopies, where vertical leaves are predominant, both sides of the leaves are assumed to be wet and to absorb the same net radiation. In the case of planophile canopies, where horizontal leaves are predominant, the lower side of the leaves is assumed to remain dry and not to absorb net radiation. The banana or plantain canopy will be considered as erectophile in its upper part and planophile in its lower part.

As for a dry canopy the whole stand is visualized as an electrical analogue where sensible and latent heat fluxes replace current (Fig.3). An erectophile layer is divided into four sublayers, two sublayers for each side of the leaves: one corresponding to the wet part of the leaves and the other corresponding to the dry part. A planophile layer is divided into three sublayers. Two correspond to the wet and dry parts of the upper side of the leaves and one corresponds to the lower side of the leaves which is assumed to remain dry. Heat is conducted from the dry part to the wet part wherever free water and dry leaf are in contact and a temperature difference exists between them.

The way that free water is deposited on leaves can differ greatly between different plant species. Moisture over the leaf surface can be deposited as a uniform film or as distinct droplets. δRn_i being the net radiation absorbed in each layer within the canopy , the part of δRn_i absorbed by wet and dry surfaces, $\delta Rn_{i,j}$, is considered as proportional

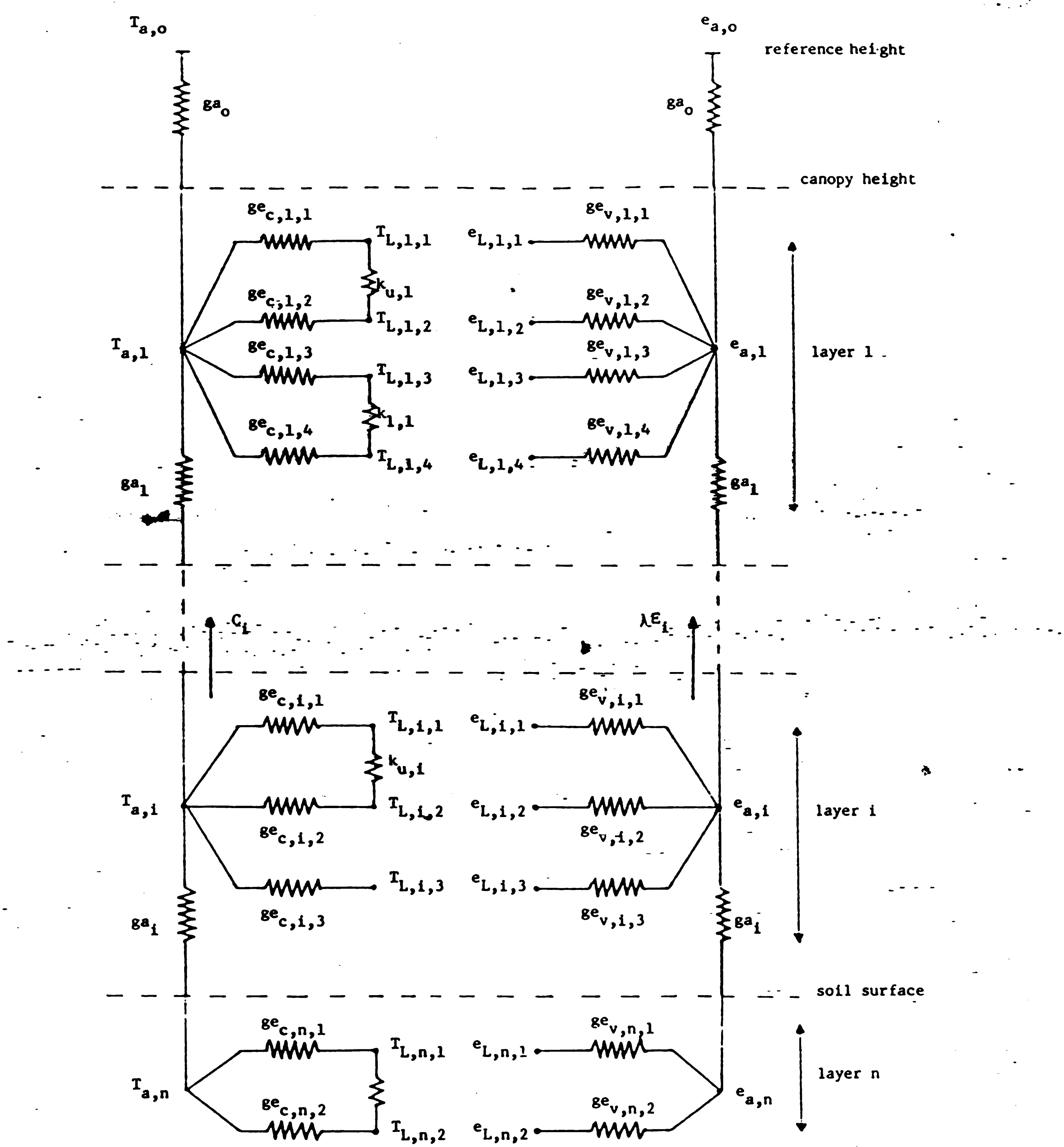

Fig. 3- Electrical analogue of exchange processes within a plant canopy with an upper part erectophile and a lower part planophile

to their areas.

The total fluxes at the top of the canopy can be expressed as a double algebraic summation over the contributions of each layer (1 to n) and each sub-layer (1 to m_i):

$$C\emptyset=\sum_{i=1}^{n}\sum_{j=1}^{mi}\delta C_{i,j} \quad , \tag{A.14}$$

$$\lambda E\emptyset=\sum_{i=1}^{n}\sum_{j=1}^{mi}\delta\lambda E_{i,j} \quad . \tag{A.15}$$

m_i equals 4 for an erectophile layer and 3 for a planophile layer.

b) Erectophile layers

If $W_{u,i}$ specifies the relative area of drops over the upper side of the leaves and $W_{l,i}$ over the lower side, for an erectophile layer divided into four sublayers, we shall write:

- for the wet part of the upper side of the leaves:

$$\delta Rn_{i,1}=W_{u,i}\delta Rn_i/2 \quad , \tag{A.16}$$

- for the dry part of the upper side:

$$\delta Rn_{i,2}=(1-W_{u,i})\delta Rn_i/2 \quad , \tag{A.17}$$

- for the wet part of the lower side:

$$\delta Rn_{i,3}=W_{l,i}\delta Rn_i/2 \quad , \tag{A.18}$$

- for the dry part of the lower side:

$$\delta Rn_{i,4}=(1-W_{l,i})\delta Rn_i/2 \quad . \tag{A.19}$$

For the soil surface (layer n), Equations (A.16) and (A.17) hold provided $\delta Rn_i/2$ is replaced by δRn_i-S, where S is the soil heat flux.

The elementary fluxes of sensible and latent heat diffusing inside layer i from sublayer j are written as:

$$\delta C_{i,j}=\rho c_p g e_{c,i,j}(T_{L,i,j}-T_{a,i}) \quad , \tag{A.20}$$

$$\delta\lambda E_{i,j}=(\rho c_p/\tau) g e_{v,i,j}(e_s(T_{L,i,j})-e_{a,i}) \quad , \tag{A.21}$$

where $ge_{c,i,j}$ and $ge_{v,i,j}$ are the equivalent conductances respectively for sensible and latent heat transfer.

For the wet part of the leaves these equivalent conductances are given by :

$$ge_{c,i,1}=ge_{v,i,1}=W_{u,i}\delta LAI_i gb_{w,i} \quad , \qquad (A.22)$$

$$ge_{c,i,3}=ge_{v,i,3}=W_{l,i}\delta LAI_i gb_{w,i} \quad , \qquad (A.23)$$

where $gb_{w,i}$ is the boundary-layer conductance of the free water assumed to be the same for sensible and latent heat; $W_{u,i}$ and $W_{l,i}$ are the relative exposed surface of free water (drop surface in contact with the air). The relative exposed surface can be slightly different from the relative surface of drop bases. This can be taken into account through an apropriate coefficient depending on drop form.

For the dry part of the leaves the equivalent conductances are given by:

$$ge_{c,i,2}=(1-W_{u,i})\delta LAI_i gb_{d,i} \quad , \qquad (A.24)$$

$$ge_{v,i,2}=(1/gs_{u,i}+1/gb_{d,i})^{-1}(1-W_{u,i})\delta LAI_i \quad , \qquad (A.25)$$

$$ge_{c,i,4}=(1-W_{l,i})\delta LAI_i gb_{d,i} \quad , \qquad (A.26)$$

$$ge_{v,i,4}=(1/gs_{l,i}+1/gb_{d,i})^{-1}(1-W_{l,i})\delta LAI_i \quad , \qquad (A.27)$$

where $gb_{d,i}$, $gs_{u,i}$ and $gs_{l,i}$ are respectively the boundary-layer conductance of the dry part of the leaves, the stomatal conductance of the upper side and the stomatal conductance of the lower side.

The soil exchange surface is one. For the wet part we have:

$$ge_{c,n,1}=ge_{v,n,1}=gb_{w,n}W_n \quad , \qquad (A.28)$$

and for the dry part:

$$ge_{c,n,2}=(1-W_n)gb_{d,n} \quad , \qquad (A.29)$$

$$ge_{v,n,2}=(1-W_n)(1/gs_n+1/gb_{d,n})^{-1} \quad , \qquad (A.30)$$

where gs_n is the surface conductance of the soil, $gb_{d,n}$ and $gb_{w,n}$ are the boundary-layer conductances of the soil surface (dry and wet parts).

Heat conduction from dry parts to wet parts of the leaves is assumed to occur accross the boundary between the dry leaf and the edge of the drop or of the film. The conduction heat fluxes can be expressed as:

$$\Phi_{u,i}=k_{u,i}(T_{L,i,2}-T_{L,i,1}) \quad , \tag{A.31}$$

$$\Phi_{l,i}=k_{l,i}(T_{L,i,4}-T_{L,i,3}) \tag{A.32}$$

where coefficients $k_{u,i}$ and $k_{l,i}$ depends on drops surface and repartition. We shall have to define the relationship between conduction coefficients and drop dimensions. Heat conducted from surrounding leaf tissue is more significant in the case of a leaf holding discrete drops than in the case of a leaf holding a continuous film.

The net radiation absorbed in each sublayer $\delta Rn_{i,j}$ balances the convective fluxes of sensible and latent heat $\delta C_{i,j}$ and $\delta\lambda E_{i,j}$ and the conductive flux:

$$\delta Rn_{i,1}=\delta C_{i,1}+\delta\lambda E_{i,1}+\Phi_{u,i} \tag{A.33}$$

$$\delta Rn_{i,2}=\delta C_{i,2}+\delta\lambda E_{i,2}-\Phi_{u,i} \tag{A.34}$$

$$\delta Rn_{i,3}=\delta C_{i,3}+\delta\lambda E_{i,3}+\Phi_{l,i} \tag{A.35}$$

$$\delta Rn_{i,4}=\delta C_{i,4}+\delta\lambda E_{i,4}-\Phi_{l,i} \tag{A.36}$$

c)Planophile layers

For a planophile layer the net radiation absorbed by the lower side of the leaves (sub-layer 3) is considered as nil:

$$\delta Rn_{i,3}=0 \quad . \tag{A.37}$$

For the wet and dry parts of the upper side we have always:

$$\delta Rn_{i,1}=W_{u,i}\delta Rn_i \quad , \tag{A.38}$$

$$\delta Rn_{i,2}=(1-W_{u,i})\delta Rn_i \quad . \tag{A.39}$$

The elementary fluxes of sensible and latent heat diffusing inside layer i are given by Equations (A.20) and (A.21). The equivalent conductances of the wet and dry parts of the upper side of the leaves (sub-layer 1 and 2) are given by Equations (A.22) and (A.24). For the lower side of the leaves (sub-layer 3) we have:

$$ge_{c,i,3}=\delta LAI_i gb_{d,i} \quad , \tag{A.40}$$

$$ge_{v,i,3}=\delta LAI_i(1/gs_{l,i}+1/gb_{d,i})^{-1} \quad . \tag{A.41}$$

The energy balance equations for each sub-layer can be written as:

$$\delta Rn_{i,1}=\delta C_{i,1}+\delta\lambda E_{i,1}+\Phi_{u,i} \quad , \tag{A.42}$$

$$\delta Rn_{i,2}=\delta C_{i,2}+\delta\lambda E_{i,2}-\Phi_{u,i} \quad , \qquad (A.43)$$

$$\delta Rn_{i,3}=\delta C_{i,3}+\delta\lambda E_{i,3} \quad . \qquad (A.44)$$

Vertical fluxes of sensible and latent heat experience a diffusive conductance, when crossing layer i, given by Equation (A.9). In both cases, erectophile and planophile, vertical fluxes emanating from layer i are given by Equations (A.10) and (A.11).

III. MATHEMATICAL RESOLUTION OF BASIC EQUATIONS

1. Expressions of total fluxes

Linearizing the saturated vapour pressure curve $e_s(T)$ by the slope Δ of the curve determined at the temperature $T_{a,0}$ of the air at the reference height, allows one to rewrite Equation (A.21) as:

$$\delta\lambda E_{i,j}=(\rho c_p/\tau)ge_{v,i,j}(\Delta(T_{L,i,j}-T_{a,i})+D_{a,i}) \quad , \qquad (B.1)$$

where $D_{a,i}$ is the vapour pressure deficit of the air in layer i:

$$D_{a,i}=e_s(T_{a,i})-e_{a,i} \qquad (B.2)$$

Putting:

$$\theta_{i,j}=T_{L,i,j}-T_{a,i} \quad , \qquad (B.3)$$

the total fluxes of sensible and latent heat can be rewritten as:

$$C_0=\rho c_p\sum_{i=1}^{n}\sum_{j=1}^{mi}ge_{c,i,j}\theta_{i,j} \quad , \qquad (B.4)$$

$$\lambda E_0=(\rho c_p/\tau)\sum_{i=1}^{n}\sum_{j=1}^{mi}ge_{v,i,j}(\Delta\theta_{i,j}+D_{a,i}) \quad . \qquad (B.5)$$

The values of $\theta_{i,j}$ can be obtained by solving simultaneously the set of energy balance equations applied to each sub-layer.

<u>Erectophile case (m_i=4):</u>

The energy balance equations can be detailed as:

$$\delta Rn_{i,1}=\rho c_p[ge_{c,i,1}\theta_{i,1}+(ge_{v,i,1}/\tau)(\Delta\theta_{i,1}+D_{a,i})]+$$
$$+k_{u,i}(\theta_{i,1}-\theta_{i,2}) \quad , \qquad (B.6)$$

$$\delta Rn_{i,2}=\rho c_p[ge_{c,i,2}\theta_{i,2}+(ge_{v,i,2}/\tau)(\Delta\theta_{i,2}+D_{a,i})]+$$
$$+k_{u,i}(\theta_{i,2}-\theta_{i,1}) \quad , \qquad (B.7)$$

$$\delta Rn_{i,3}=\rho c_p[ge_{c,i,3}\theta_{i,3}+(ge_{v,i,3}/\tau)(\Delta\theta_{i,3}+D_{a,i})]+$$
$$+k_{l,i}(\theta_{i,3}-\theta_{i,4}) \quad , \qquad (B.8)$$

$$\delta Rn_{i,4}=\rho c_p[ge_{c,i,4}\theta_{i,4}+(ge_{v,i,4}/\tau)(\Delta\theta_{i,4}+D_{a,i})]+ +k_{l,i}(\theta_{i,4}-\theta_{i,3}) \quad . \tag{B.9}$$

Putting:

$$a_{i,j}=ge_{c,i,j}+(\Delta/\tau)ge_{v,i,j} \quad , \tag{B.10}$$

$$d_{u,i}=a_{i,1}a_{i,2}+(k_{u,i}/\rho c_p)(a_{i,1}+a_{i,2}) \quad , \tag{B.11}$$

$$d_{l,i}=a_{i,3}a_{i,4}+(k_{l,i}/\rho c_p)(a_{i,3}+a_{i,4}) \quad , \tag{B.12}$$

we obtain, taking into account Equations (A.16) to (A.19):

$$\theta_{i,j}=P_{i,j}\delta Rn_i/\rho c_p-Q_{i,j}D_{a,i}/\tau \tag{B.13}$$

with:

$$P_{i,1}=(W_{p,u,i}a_{i,2}/2+k_{u,i}/\rho c_p)/d_{u,i} \tag{B.14}$$

$$Q_{i,1}=[a_{i,2}ge_{v,i,1}+(k_{u,i}/\rho c_p)(ge_{v,i,1}+ge_{v,i,2})]/d_{u,i} \tag{B.15}$$

$$P_{i,2}=[(1-W_{p,u,i})a_{i,1}/2+k_{u,i}/\rho c_p]/d_{u,i} \tag{B.16}$$

$$Q_{i,2}=[a_{i,1}ge_{v,i,2}+(k_{u,i}/\rho c_p)(ge_{v,i,1}+ge_{v,i,2})]/d_{u,i} \tag{B.17}$$

$$P_{i,3}=(W_{p,l,i}a_{i,4}/2+k_{l,i}/\rho c_p)/d_{l,i} \tag{B.18}$$

$$Q_{i,3}=[a_{i,4}ge_{v,i,3}+(k_{l,i}/\rho c_p)(ge_{v,i,3}+ge_{v,i,4})]/d_{l,i} \tag{B.19}$$

$$P_{i,4}=[(1-W_{p,l,i})a_{i,3}/2+k_{l,i}/\rho c_p]/d_{l,i} \tag{B.20}$$

$$Q_{i,4}=[a_{i,3}ge_{v,i,4}+(k_{l,i}/\rho c_p)(ge_{v,i,3}+ge_{v,i,4})]/d_{l,i} \tag{B.21}$$

Planophile case ($m_i=3$):

The energy balance equations are written as:

$$\delta Rn_{i,1}=\rho c_p[ge_{c,i,1}\theta_{i,1}+(ge_{v,i,1}/\tau)(\Delta\theta_{i,1}+D_{a,i})]+ +k_i(\theta_{i,1}-\theta_{i,2}) \quad , \tag{B.22}$$

$$\delta Rn_{i,2}=\rho c_p[ge_{c,i,2}\theta_{i,2}+(ge_{v,i,2}/\tau)(\Delta\theta_{i,2}+D_{a,i})]+ +k_i(\theta_{i,2}-\theta_{i,1}) \quad , \tag{B.23}$$

$$0=\rho c_p[ge_{c,i,3}\theta_{i,3}+(ge_{v,i,3}/\tau)(\Delta\theta_{i,3}+D_{a,i})] \quad . \tag{B.24}$$

Putting:

$$a_{i,j}=ge_{c,i,j}+(\Delta/\tau)ge_{v,i,j} \quad , \tag{B.25}$$

$$d_{u,i}=a_{i,1}a_{i,2}+(k_i/\rho c_p)(a_{i,1}+a_{i,2}) , \quad (B.26)$$

we obtain:

$$\theta_{i,j}=P_{i,j}\delta Rn_i/\rho c_p-Q_{i,j}D_{a,i}/\tau , \quad (B.27)$$

where:

$$P_{i,1}=(W_{p,u,i}a_{i,2}+k_{u,i}/\rho c_p)/d_{u,i} , \quad (B.28)$$

$$Q_{i,1}=[a_{i,2}ge_{v,i,1}+(k_{u,i}/\rho c_p)(ge_{v,i,1}+ge_{v,i,2})]/d_{u,i} \quad (B.29)$$

$$P_{i,2}=[(1-W_{p,u,i})a_{i,1}+k_{u,i}/\rho c_p]/d_{u,i} , \quad (B.30)$$

$$Q_{i,2}=[a_{i,1}ge_{v,i,2}+(k_{u,i}/\rho c_p)(ge_{v,i,1}+ge_{v,i,2})]/d_{u,i} \quad (B.31)$$

$$P_{i,3}=0 , \quad (B.32)$$

$$Q_{i,3}=ge_{v,i,3}/a_{i,3} . \quad (B.33)$$

Replacing $\theta_{i,j}$ in Equations (B.4) and (B.5) by Equation (B.13) or (B.27) yields:

$$C\emptyset=\sum_{i=1}^{n}\sum_{j=1}^{mi}ge_{c,i,j}P_{i,j}\delta Rn_i-(\rho c_p/\tau)\sum_{i=1}^{n}\sum_{j=1}^{mi}ge_{c,i,j}Q_{i,j}D_{a,i} \quad (B.34)$$

$$\lambda E\emptyset=(\Delta/\tau)\sum_{i=1}^{n}\sum_{j=1}^{mi}ge_{v,i,j}P_{i,j}\delta Rn_i+$$

$$+(\rho c_p/\tau)\sum_{i=1}^{n}\sum_{j=1}^{mi}ge_{v,i,j}(1-(\Delta/\tau)Q_{i,j})D_{a,i} . \quad (B.35)$$

At this stage it can be proven that:

$$\sum_{j=1}^{mi}ge_{v,i,j}(1-(\Delta/\tau)Q_{i,j})=\sum_{j=1}^{mi}ge_{c,i,j}Q_{i,j} . \quad (B.36)$$

Defining:

$$\mu_{c,i}=\sum_{j=1}^{mi}ge_{c,i,j}P_{i,j} , \quad (B.37)$$

$$\mu_{v,i}=\sum_{j=1}^{mi}ge_{v,i,j}P_{i,j} , \quad (B.38)$$

$$\pi_i = \sum_{j=1}^{mi} ge_{c,i,j} Q_{i,j} \ , \qquad (B.39)$$

Equations (B.34) and (B.35) can be rewritten as:

$$C_\emptyset = \sum_{i=1}^{n} \mu_{c,i} \delta Rn_i - (\rho c_p/\tau) \sum_{i=1}^{n} \pi_i D_{a,i} \ , \qquad (B.40)$$

$$\lambda E_\emptyset = (\Delta/\tau) \sum_{i=1}^{n} \mu_{v,i} \delta Rn_i + (\rho c_p/\tau) \sum_{i=1}^{n} \pi_i D_{a,i} \ . \qquad (B.41)$$

2. Recurrent formulae for the calculation of $D_{a,i}$

At each node of the circuit, caracterized by potentials $T_{a,i}$ and $e_{a,i}$, elementary horizontal fluxes $\delta C_{i,j}$ and $\delta\lambda E_{i,j}$ mix with main vertical fluxes C_{i+1} and λE_{i+1} emanating from lower layers. For each node it is possible to write one of the following conservation equations:

$$C_i = C_{i+1} + \sum_{j=1}^{mi} \delta C_{i,j} \ , \qquad (B.42)$$

$$\lambda E_i = \lambda E_{i+1} + \sum_{j=1}^{mi} \delta\lambda E_{i,j} \ . \qquad (B.43)$$

Developping these equations yields respectively:

$$ga_{i-1}(T_{a,i} - T_{a,i-1}) = ga_i(T_{a,i+1} - T_{a,i}) +$$

$$+ \sum_{j=1}^{mi} ge_{c,i,j}(T_{L,i,j} - T_{a,i}) \ , \qquad (B.44)$$

$$ga_{i-1}(e_{a,i} - e_{a,i-1}) = ga_i(e_{a,i+1} - e_{a,i}) +$$

$$+ \sum_{j=1}^{mi} ge_{v,i,j}(e_s(T_{L,i,j}) - e_{a,i}) \ . \qquad (B.45)$$

Multiplying Equation (B.44) by Δ gives:

$$g a_{i-1}[e_s(T_{a,i})-e_s(T_{a,i-1})]=g a_i[e_s(T_{a,i+1})-e_s(T_{a,i})]+$$

$$+\sum_{j=1}^{mi} g e_{c,i,j}[e_s(T_{L,i,j})-e_s(T_{a,i})] \quad (B.46)$$

Equations (B.45) and (B.46) can be rewritten respectively as:

$$e_{a,i+1}=(1-b_i)e_{a,i}+b_i e_{a,i-1}+\sum_{j=1}^{mi} c_{v,i,j}[e_s(T_{L,i,j})-e_{a,i}] \quad (B.47)$$

$$e_s(T_{a,i+1})=(1-b_i)e_s(T_{a,i})+b_i e_s(T_{a,i-1})+$$

$$+\sum_{j=1}^{mi} c_{c,i,j}[e_s(L,i,j)-e_s(T_{a,i})] \quad , \quad (B.48)$$

with:

$$b_i=-g a_{i-1}/g a_i \; , \quad (B.49)$$

$$c_{c,i,j}=-g e_{c,i,j}/g a_i \; , \quad (B.50)$$

$$c_{v,i,j}=-g e_{v,i,j}/g a_i \; . \quad (B.51)$$

Multiplying Equation (B.13) or (B.27) by Δ gives:

$$e_s(T_{L,i,j})-e_s(T_{a,i})=\Delta P_{i,j}\delta Rn_i/\rho c_p-(\Delta/\tau)Q_{i,j}D_{a,i} \; , (B.52)$$

which enables one to rewrite Equations (B.47) and (B.48) as follows:

$$e_{a,i+1}=(1-b_i)e_{a,i}+b_i e_{a,i-1}+\Delta\sum_{j=1}^{mi} c_{v,i,j}P_{i,j}\delta Rn_i/\rho c_p-$$

$$-(\Delta/\tau)\sum_{j=1}^{mi} c_{v,i,j}Q_{i,j}D_{a,i}+\sum_{j=1}^{mi} c_{v,i,j}D_{a,i} \; , \quad (B.53)$$

$$e_s(T_{a,i+1})=(1-b_i)e_s(T_{a,i})+b_i e_s(T_{a,i-1})+$$

$$+\Delta\sum_{j=1}^{mi} c_{c,i,j}P_{i,j}\delta Rn_i/\; c_p-(\Delta/\tau)\sum_{j=1}^{mi} c_{c,i,j}Q_{i,j}D_{a,i} \; . (B.54)$$

Substracting Equation (B.53) from Equation (B.54) yields the following recurrent relation for saturation deficit $D_{a,i}$:

$$D_{a,i+1}=a_i D_{a,i}+b_i D_{a,i-1}+c_i\delta Rn_i/\rho c_p \; , \quad (B.55)$$

with:

$$a_i=1-b_i-\sum_{j=1}^{mi}c_{v,i,j}+(\Delta/\tau)\sum_{j=1}^{mi}(c_{v,i,j}-c_{c,i,j})Q_{i,j} \ , \qquad (B.56)$$

$$c_i=\Delta\sum_{j=1}^{mi}(c_{c,i,j}-c_{v,i,j})P_{i,j} \ . \qquad (B.57)$$

The first term of the recurrent process $D_{a,1}$ represents the vapour pressure-deficit of the air at the top of the canopy. The second term is written as:

$$D_{a,2}=a_1D_{a,1}+\Delta J_\emptyset/\rho c_p g a_1+c_1\delta Rn_1/\rho c_p \ , \qquad (B.58)$$

with:

$$a_1=1-\sum_{j=1}^{mi}c_{v,1,j}+(\Delta/\tau)\sum_{j=1}^{mi}(c_{v,1,j}-c_{c,1,j})Q_{1,j} \ , \qquad (B.59)$$

$$c_1=\Delta\sum_{j=1}^{mi}(c_{c,1,j}-c_{v,1,j})P_{1,j} \ , \qquad (B.60)$$

$$J_\emptyset=C_\emptyset-(\tau/\Delta)\lambda E_\emptyset \ . \qquad (B.61)$$

For any subscript i, $D_{a,i}$ can be put in the form:

$$D_{a,i}=\alpha_iD_{a,1}+\beta_i\Delta J_\emptyset/\rho c_p g a_1+\sum_{k=1}^{i-1}\epsilon_i^k\delta Rn_k/\rho c_p \ , \qquad (B.62)$$

coefficients α_i, β_i and ϵ_i being calculated by means of the following recurrent formulae:

$$\alpha_{i+1}=a_i\alpha_i+b_i\alpha_{i-1} \ ; \qquad (B.63)$$

$$\beta_{i+1}=a_i\beta_i+b_i\beta_{i-1} \ , \qquad (B.64)$$

$$\epsilon_{i+1}^{k\leq i-1}=a_i\epsilon_i^k+b_i\epsilon_{i-1}^k \ , \qquad (B.65)$$

$$\epsilon_{i+1}^{i-1}=a_i\epsilon_i^{i-1}=a_ic_{i-1} \ , \qquad (B.66)$$

$$\epsilon_{i+1}^i=c_i \ , \qquad (B.67)$$

and the first coefficients being defined as:

$$\alpha_1=1 \ , \quad \beta_1=0 \ , \quad \alpha_2=a_1 \ , \quad \beta_2=1 \ , \quad \epsilon_2^1=c_1 \ . \qquad (B.68)$$

The total flux density of latent heat at the top of the canopy can be written as (Slatyer and McIlroy, 1961; Monteith, 1981):

$$\lambda E_\emptyset=[\Delta(Rn_\emptyset-S)+\rho c_p g a_\emptyset(D_{a,o}-D_{a,1})]/(\Delta+\tau) \ , \qquad (B.69)$$

where $D_{a,\emptyset}$ is the saturation deficit of the air at a reference height above the canopy and $ga_{\emptyset}$ is the aerodynamic conductance calculated between the top of the canopy and the reference height. Expressing $D_{a,1}$ as a function of $D_{a,\emptyset}$ from Equation (B.69) and taking into account the energy balance equation:

$$Rn_{\emptyset}-S=C_{\emptyset}+\lambda E_{\emptyset} \ , \tag{B.70}$$

Equation (B.62) turns into:

$$D_{a,i}=\alpha_i D_{a,\emptyset}+(\alpha_i/ga_{\emptyset}+\beta_i/ga_1)\Delta J_{\emptyset}/\rho c_p+\sum_{k=1}^{i-1}\epsilon_1^k \delta Rn_k/\rho c_p \tag{B.71}$$

3. Total flux densities of sensible and latent heat

Substituting Equation (B.71) into Equations (B.40) and (B.41) and defining:

$$A=\sum_{i=1}^{n}\pi_i\alpha_i/ga_{\emptyset} \ , \tag{B.72}$$

$$B=\sum_{i=1}^{n}\pi_i\beta_i/ga_1 \ , \tag{B.73}$$

we obtain respectively:

$$C_{\emptyset}=[\tau+(\Delta+\tau)(A+B)]-[\tau(A+B(Rn_{\emptyset}-S)-\rho c_p ga_{\emptyset}AD_{a,\emptyset}]=$$

$$=\sum_{i=1}^{n}(\tau\mu_{c,i}\delta Rn_i-\pi_i\sum_{k=1}^{i-1}\epsilon_1^k\delta Rn_k) \ , \tag{B.74}$$

$$\lambda E_{\emptyset}[\tau+(\Delta+\tau)(A+B)]-[\Delta(A+B)(Rn_{\emptyset}-S)+\rho c_p ga_{\emptyset}AD_{a,\emptyset}]=$$

$$=\sum_{i=1}^{n}(\Delta\mu_{v,i}\delta Rn_i+\pi_i\sum_{k=1}^{i-1}\epsilon_1^k\delta Rn_k) \ . \tag{B.75}$$

Putting:

$$\epsilon_1^i=\Delta\mu_{v,i}/\pi_i \ , \tag{B.76}$$

the right hand terms of Equations (B.74) and (B.75) can be rewritten respectively as:

$$\sum_{i=1}^{n}(\tau\mu_{c,i}\delta Rn_i+\Delta\mu_{v,i}\delta Rn_i-\pi_i\sum_{k=1}^{i}\epsilon_1^k\delta Rn_k) \ , \tag{B.77}$$

$$\sum_{i=1}^{n}\pi_i\sum_{k=1}^{i}\epsilon_1^k \ \delta Rn_k \ . \tag{B.78}$$

Noticing that:

$$\sum_{i=1}^{n}(\tau\mu_{c,i}+\Delta\mu_{v,i})\delta Rn_i=\tau(Rn_\emptyset-S) \ , \qquad (B.79)$$

$$\sum_{i=1}^{n}\pi_i\sum_{k=1}^{i}\epsilon_i^k\delta Rn_k=\sum_{i=1}^{n}(\sum_{k=i}^{n}\pi_k\epsilon_k^i)\delta Rn_i \ , \qquad (B.80)$$

and defining:

$$E_i=\sum_{k=i}^{n}\pi_k\,\epsilon_k^i \ , \qquad (B.81)$$

Equations (B.74) and (B.75) become:

$$C_\emptyset=\frac{\tau(1+A+B)(Rn_\emptyset-S)-\sum_{i=1}^{n}E_i\delta Rn_i-\rho c_p g a_\emptyset AD_{a,\emptyset}}{\tau+(\Delta+\tau)(A+B)} \ , \qquad (B.82)$$

$$\lambda E_\emptyset=\frac{(A+B)(Rn_\emptyset-S)+\sum_{i=1}^{n}E_i\delta Rn_i+\rho c_p g a_\emptyset AD_{a,\emptyset}}{\tau+(\Delta+\tau)(A+B)} \ . \qquad (B.83)$$

It is possible to transform Equations (B.82) and (B.83) so that they have the same formalism as the classical Penman's formulae (Penman, 1948, 1953). We shall define the fraction of net radiation absorbed in layer i, p_i, as:

$$p_i=\delta Rn_i/(Rn_\emptyset-S) \ . \qquad (B.84)$$

p_i can be easily calculated assuming available radiative energy Rn(z)-S to decrease as an exponential function of the cumulative leaf area index L(z):

$$Rn(z)-S=(Rn_\emptyset-S)\exp[-\alpha_\emptyset L(z)] \ . \qquad (B.85)$$

Coefficient $\alpha_\emptyset$ has to be slightly different from the one used in the familiar exponential decrease of net radiation because of the soil heat flux term. From this type of equation it is possible to infer the following expression of p_i:

$$p_i=\alpha_\emptyset\exp[-\alpha_\emptyset\sum_{j=1}^{i-1}\delta LAI_j]\delta LAI_i \ . \qquad (B.86)$$

Putting:

$$\tau^*=\tau(1+A+B)-\sum_{i=1}^{n} E_i p_i \ , \qquad (B.87)$$

$$\Delta^*=\Delta(A+B)+\sum_{i=1}^{n} E_i p_i \ , \qquad (B.88)$$

$$ga_\emptyset^*=ga_\emptyset A \ , \qquad (B.89)$$

Equations (B.82) and (B.83) can be rewritten as:

$$C_\emptyset=\frac{\tau^*(Rn_\emptyset-S)-\rho c_p ga_\emptyset^* D_{a,\emptyset}}{\Delta^*+\tau^*} \ , \qquad (B.90)$$

$$\lambda E_\emptyset=\frac{\Delta^*(Rn_\emptyset-S)+\rho c_p ga_\emptyset^* D_{a,\emptyset}}{\Delta^*+\tau^*} \ . \qquad (B.91)$$

4.Calculation of microclimatic profiles

Micrometeorological profiles and evaporation from each sublayer can be calculated once total fluxes $C_\emptyset$ and $\lambda E_\emptyset$ are determined. All elementary conductances are assumed to be known as also the profile of net radiation, the soil heat flux, the net radiation and the vapour pressure deficit of the air at a reference height.

The vapour pressure deficit at the top of the canopy $D_{a,1}$ is calculated from Equation (B.69). Then the following recurrent process is used. Knowing net radiation δRn_i and saturation deficit $D_{a,i}$ in layer i, $\theta_{i,j}$ (j=1 to 4) is determined from Equation (B.13) or (B.27). So, elementary fluxes of sensible and latent heat emanating from each sublayer and from water drops in particular can be calculated from Equations (A.20) and (A.21). Knowing the vertical fluxes C_i and λE_i at the upper boundary of layer i and the horizontal fluxes $\delta C_{i,j}$ and $\delta\lambda E_{i,j}$ in the same layer i, the vertical fluxes at the lower boundary δC_{i+1} and $\delta\lambda E_{i+1}$ are calculated by means of conservation Equations (B.42) and (B.43). And air characteristics in layer i+1 (T_a,e_a) are determined from Equations (A.10) and (A.11). The same recurrent process is used for layer i+1 and so on down to the soil surface.

IV.PARAMETERIZATIONS USED IN THE MODEL

1.Profiles linked with mecanic transfers

Above the canopy, assuming we are close to neutral conditions, we shall use the classical log-profile of wind velocity u as a function of height z:

$$u(z)=(u_*/k)\ln[(z-d)/z_0] \quad (C.1)$$

where u_* is the friction velocity, k is the von Karman constant (0.4), d is the zero plane displacement and z_0 is the roughness length. d and z_0 are given by the following empirical formulae where z_h is the canopy height:

$$d=0.75z_h \quad (C.2)$$

$$z_0=0.13z_h \quad (C.3)$$

Eddy diffusivity K(z) is given by the classical formula:

$$K(z)=ku_*(z-d) \quad (C.4)$$

And the aerodynamic conductance ga_0, calculated between the top of the canopy (z_h) and the reference height (z_r) is given by:

$$ga_0=1/\int_{z_h}^{z_r}(1/K(z))dz=ku_*/\ln[(z_r-d)/(z_h-d)] \quad (C.5)$$

Within the canopy various profiles of wind velocity and eddy diffusivity have been derived by different authors from theoretical considerations or experimental results. It is generally common to use exponential decreases with depth in the form:

$$u(z)=u(z_h)\exp[-\alpha_u(1-z/z_h)] \quad (C.6)$$

$$K(z)=K(z_h)\exp[-\alpha_k(1-z/z_h)] \quad (C.7)$$

The best values of α for numerous canopies lies between 2 and 4 (Cionco, 1965; Brown and Covey, 1966; Cionco, 1972).

As to the boundary layer conductance of the leaves (gb) we shall use a classical formulation as a function of wind velocity (u) and leaf width (l):

$$gb=a_0(u/l)^{0.5} \quad (C.8)$$

A typical value of $a_\emptyset$ is 1/300 (Monteith, 1973). The boundary layer conductance of the drops is considered as independant of drop size and the mean value is about twice that of the leaf (Butler, 1985).

2. Radiative profiles

Global radiation Rg and net radiation Rn are assumed to decrease as exponential functions of the downward cumulative leaf area index L(z), which is related to leaf area density l(z) by:

$$L(z)=\int_{z}^{z_h} l(z)dz \qquad (C.9)$$

We shall write then:

$$Rg(z)=Rg(z_h)\exp(-\alpha_g L(z)) \qquad (C.10)$$

$$Rn(z)=Rn(z_h)\exp(-\alpha_n L(z)) \qquad (C.11)$$

attenuation coefficients α_g and α_n can be considered as equal for the two profiles. For most canopies exponential extinctions work reasonably well with a coefficient lying between 0.4 and 0.7.

At the bottom of the canopy one part of the net radiation reaching the ground Rn(0) is dissipated to the air as sensible and latent heat. The other part is lost from the canopy system as heat flux into the soil:

$$S=c.Rn(0) \qquad (C.12)$$

c is close to 0.5 (Butler, 1986).

3. Stomatal conductance profile

To describe the stomatal conductance profiles for each side of the leaves, a simple parameterization as a linear function of global radiation can be used. It is useless to take into account the influence of water stess on stomatal conductance since the model is always run in rainy conditions. If gs_n specifies the minimum value and gs_x the maximum value of stomatal conductance corresponding respectively to a lower limit Rg_n and an upper limit Rg_x of global radiation , we shall write:

$$gs(z)-gs_n=(gs_x-gs_n)(Rg(z)-Rg_n)/(Rg_x-Rg_n) \qquad (C.13)$$

The different parameters have to be derived experimentally. In the case of a banana or plantain canopy, given that the number of stomata on the upper side of the leaves is very small, we can assume a constant profile on the upper side close to a complete closing.

The soil resistance to water vapour transfer can be taken as zero assuming the soil surface to be saturated, since the model is intended to be used in rainy conditions..

4.Heat conduction

To parameterize heat conduction fluxes between dry and wet parts of the leaves we use a simple model assuming the conduction flux to be proportional to the circumference of the drop base:

$$k=\eta\pi d \qquad (C.14)$$

where d is the base diameter of the drop and η the effective conduction coefficient. We shall also assume free water over the leaves to form a single big circular drop with an area of A. The relationship between d and A is:

$$d=2(A/\pi)^{1/2} \qquad (C.15)$$

Foe each wet sublayer, A is equal to the partial leaf area index δLAI_i multiplied by the relative surface of free water W_i. Hence conduction coefficients can be written as:

$$k_{u,i}=2\eta(\pi W_{u,i}\delta LAI_i)^{1/2} \qquad (C.16)$$

$$k_{l,i}=2\eta(\pi W_{l,i}\delta LAI_i)^{1/2} \qquad (C.17)$$

According to Butler (1985) the value of η is close to 0.1 $Wm^{-1}K^{-1}$.

5.Model operation and resorption relationship

To estimate the persistence of free water on the leaves the model of evaporation must be running assuming a succession of steady state conditions. For each period the values of global radiation, net radiation, air temperature, air humidity and wind velocity at a reference height are required. Net radiation is calculated as a given fraction of global radiation. New drop volumes and dimensions are calculated by substracting for each sublayer the water evaporated during the time step t from the drop volume at the beginning of the time step.

Equations relating drop volume V to wet surface W are given by Butler (1985) for wheat leaves and by Leclerc and al.(1985) for artificial soybean leaves. In a general way it is always possible to use an equation of the form (Huber,1988):

$$W=aV^{\beta} \tag{C.18}$$

where β is the resorption coefficient, the value of which has to be experimentally derived. $\beta=1$ corresponds to an evaporation with a constant drop or film thickness, $0<\beta<1$ corresponds to an evaporation where wet surface decreases simultaneously with thickness. Hence, wet surface variation between time steps t and t+1 can be expressed as:

$$W_{t+1}/W_t=(V_{t+1}/V_t)^{\beta} \tag{C.19}$$

V.SIMULATION PROGRAM

1.Programming aspects

A simulation program was written in Fortran 77. It works in the following way. The input data are read in 4 files: CANOPY, PARAMET, STOMATA and WEATHER.

In CANOPY file the program reads the characteristics of the canopy:
-ZH, (z_h) is the canopy height,
-NL, (n) is the number of layers,
-CW, (l) is the leaf width,
-DZ(), (δz) is the thickness of each layer
-DLAI(), (δLAI) is the partial leaf area index of each layer
-NSL(), (m) is the number of sub-layers in each layer, 4 if the layer is erectophile and 3 if the layer is planophile,
-VU(), is the volume of free water on the upper side of the leaves in each layer,
-WU(), is the percentage of wet surface on the upper of the leaves in each layer,
-VL(), is the volume of free water on the lower side of the leaves in each layer,
-WL(), is the percentage of wet surface on the lower side of the leaves in each layer,

In PARAMET file the program reads the values of the parameters used in the submodels:
-ALG, (α_g) is used in submodel global radiation profile (Eq.C.10),
-ALN, (α_n) is used in submodel net radiation profile (Eq.C.11),
-COE, (c) is used in the calculation of the soil heat flux (Eq.C.12),
-ALU, (α_u) is used in wind profile submodel (Eq.C.6),
-ALK, (α_k) is used in diffusivity profile submodel (Eq.C.7),
-AAD, ($a_\emptyset$) is used in dry parts boundary-layer conductance submodel (Eq.C.8),
-AAW, ($a_\emptyset$) is used in wet parts boundary-layer conductance submodel (Eq.C.8),
-AAB, (β) is used in resorption submodel (Eq.C.18),
-XKK, (κ) is used in heat conduction submodel (Eqs.C.16 and C.17).

In STOMATA file the program reads the values of the parameters used in the parameterization of the stomatal profile (Eq.C.13):
-GSN, (gs_n) is the minimum value of leaf stomatal conductance,
-GSX, (gs_x) is the maximum value of leaf stomatal conductance,
-RGN, (Rg_n) is the global radiation corresponding to gs_n,

-RGX, (Rg_x) is the global radiation corresponding to gs_x,
-GSUP, is the constant value of the stomatal conductance of the upper side of the leaves.

In WEATHER file the program reads the meteorological data corresponding to each time step:
-TISTEP is the duration of the time step in minutes, constant for all the simulation process,
-ZR is the reference height where meteorological data are taken,
-NSTEP is the number of the time step,
-TAØ is the air temperature at the reference height,
-EAØ is the water vapour pressure of the air at the reference height,
-UØ is the wind velocity at the reference height,
-RGØ is the global radiation.

The results of the simulation are printed in RESULTS and DURA files. In RESULTS file, for each time step, we give: the components of the energy balance, the wind velocity profile, the stomatal resistance profile, the air temperature profile, the profiles of interception (free water volume and percentage of wet surface) and the profile of leaf temperature. In DURA file we give the wetness duration profiles of the upper and lower sides of the leaves, expressed in mn.

2.Program listing

```
C  ***  PROGRAM WETDU  ***
      REAL LEØ,LEI,LAM,MUV
      DIMENSION DZ(1Ø),DLAI(1Ø),NSL(1Ø),VU(1Ø),VL(1Ø)
      DIMENSION WU(1Ø),WL(1Ø),RG(1Ø),DRN(1Ø),U(1Ø),TA(1Ø)
      DIMENSION EA(1Ø),HR(1Ø),DA(1Ø),GA(1Ø),DELRN(1Ø,4)
      DIMENSION GBD(1Ø),GBW(1Ø),GSU(1Ø),GSL(1Ø),RSL(1Ø)
      DIMENSION GEC(1Ø,4),GEV(1Ø,4),DC(1Ø,4),DLE(1Ø,4)
      DIMENSION CV(1Ø,4),CC(1Ø,4),XKU(1Ø),XKL(1Ø),TL(1Ø,4)
      DIMENSION XA(1Ø,4),DDU(1Ø),DDL(1Ø),MUV(1Ø),PI(1Ø)
      DIMENSION A(1Ø),B(1Ø),C(1Ø),AL(1Ø),BE(1Ø),EP(1Ø,1Ø)
      DIMENSION SIGE(1Ø),PP(1Ø,4),QQ(1Ø,4),WDU(1Ø),WDL(1Ø)
C  ***  GAM  PSYCHROMETRIC CONSTANT (Pa) ***
C  ***  RCP  HEAT CAPACITY OF THE AIR (J/m3/K)  ***
C  ***  LAM  LATENT HEAT OF VAPORIZATION (J/g)  ***
      GAM=66.
      RCP=117Ø.
      LAM=24ØØ.
      OPEN(5,FILE='CANOPY',STATUS='OLD')
      OPEN(6,FILE='PARAMET',STATUS='OLD')
      OPEN(7,FILE='STOMATA',STATUS='OLD')
      OPEN(8,FILE='WEATHER',STATUS='OLD')
      OPEN(9,FILE='RESULTS',STATUS='NEW')
C  ***  ZH      CANOPY HEIGHT (m)  ***
```

```
C   ***  NL       NUMBER OF LAYERS  ***
C   ***  DZ()     LAYER THICKNESS (m) ***
C   ***  DLAI()   LEAF AREA INDEX OF EACH LAYER (m2/m2) ***
C   ***  NSL()    NUMBER OF SUBLAYERS IN EACH LAYER ***
C   ***  VU()     FREE WATER VOLUME ON THE UPPER SIDE OF THE
C   ***           LEAVES IN EACH LAYER (mm)  ***
C   ***  VL()     FREE WATER VOLUME ON THE LOWER SIDE OF THE
C   ***           LEAVES IN EACH LAYER  ***
C   ***  WU()     PERCENTAGE OF WET SURFACE ON THE UPPER SIDE
C   ***           OF THE LEAVES IN EACH LAYER (%)  ***
C   ***  WL()     PERCENTAGE OF WET SURFACE ON THE LOWER SIDE
C   ***           OF THE LEAVES IN EACH LAYER (%)
C   ***  TISTEP   TIME STEP (mn) ***
C   ***  ZR       REFERENCE HEIGHT (m) ***
C   ***  NSTEP    NUMBER OF THE STEP ***
C   ***  TAØ      AIR TEMPERATURE (C) ***
C   ***  EAØ      AIR WATER VAPOUR PRESSURE (Pa) ***
C   ***  UØ       WIND VELOCITY (m/s) ***
C   ***  RGØ      GLOBAL RADIATION (W/m2) ***
      READ(5,*)ZH,NL,CW
      NN=NL+1
      READ(5,*)(DZ(I),I=1,NL)
      READ(5,*)(DLAI(I),I=1,NL)
      READ(5,*)(NSL(I),I=1,NL)
      READ(5,*)(VU(I),I=1,NN)
      READ(5,*)(WU(I),I=1,NN)
      READ(5,*)(VL(I),I=1,NN)
      READ(5,*)(WL(I),I=1,NN)
      DO 1 I=1,NN
      WDU(I)=Ø
      WDL(I)=Ø
      VU(I)=VU(I)*DLAI(I)
    1 VL(I)=VL(I)*DLAI(I)
      READ(6,*)ALG,ALN,COE,ALU,ALK,AAD,AAW,AAB,XKK
      READ(7,*)GSN,GSX,RGN,RGX,GSUP
      READ(8,*)TISTEP,ZR
    2 READ(8,*,END=99)NSTEP,UØ,RGØ,TAØ,EAØ
      RNØ=.6*RGØ
      DAØ=ES(TAØ)-EAØ
      DEL=ES(TAØ+1)-ES(TAØ)
      CALL RAD(RG,DRN,S,NL,RGØ,RNØ,DLAI,ALN,ALG,COE)
      CALL AEREO(GAØ,UZH,EDZH,UØ,ZR,ZH)
      CALL WIND(U,GA,DZ,NL,ZH,UZH,EDZH,ALU,ALK)
      CALL BOLA(U,GBD,GBW,NL,AAD,AAW,CW)
      CALL STOMA(GSU,GSL,RG,NL,GSN,GSX,RGN,RGX,GSUP)
C   ***  PHYSICAL EQUATIONS  ***
      GSL(NN)=.Ø1
      GSU(NN)=.Ø1
      GBW(NN)=GBW(NL)
      GBD(NN)=GBD(NL)
      DLAI(NN)=1.
      NSL(NN)=2
      DO 22 I=1,NN
      WU(I)=AMIN1(WU(I),99.)
```

```
      WL(I)=AMIN1(WL(I),99.)
      WU(I)=.01*WU(I)
      WL(I)=.01*WL(I)
      XKU(I)=2*XKK*SQRT(3.14*WU(I)*DLAI(I))
      XKL(I)=2*XKK*SQRT(3.14*WL(I)*DLAI(I))
      RSL(I)=1/GSL(I)
      IF(NSL(I).LE.3) THEN
C  ***  PLANOPHILE LAYER ***
      DELRN(I,1)=WU(I)*DRN(I)
      DELRN(I,2)=(1-WU(I))*DRN(I)
      DELRN(I,3)=0.
      GEC(I,1)=GBW(I)*WU(I)*DLAI(I)
      GEC(I,2)=GBD(I)*(1-WU(I))*DLAI(I)
      GEC(I,3)=GBD(I)*DLAI(I)
      GEV(I,1)=GEC(I,1)
      GEV(I,2)=(GBD(I)*GSU(I))/(GBD(I)+GSU(I))
      GEV(I,2)=GEV(I,2)*(1-WU(I))*DLAI(I)
      GEV(I,3)=(GBD(I)*GSL(I))/(GBD(I)+GSL(I))*DLAI(I)
      DO 5 J=1,3
    5 XA(I,J)=GEC(I,J)+(DEL/GAM)*GEV(I,J)
      IF(WU(I))8,8,6
    6 DDU(I)=XA(I,1)*XA(I,2)+(XKU(I)/RCP)*(XA(I,1)+XA(I,2))
      PP(I,1)=(WU(I)*XA(I,2)+XKU(I)/RCP)/DDU(I)
      PP(I,2)=((1-WU(I))*XA(I,1)+XKU(I)/RCP)/DDU(I)
      PP(I,3)=0.
      GV=(GEV(I,1)+GEV(I,2))*XKU(I)/RCP
      QQ(I,1)=(XA(I,2)*GEV(I,1)+GV)/DDU(I)
      QQ(I,2)=(XA(I,1)*GEV(I,2)+GV)/DDU(I)
      QQ(I,3)=GEV(I,3)/XA(I,3)
      GO TO 20
    8 PP(I,1)=0.
      QQ(I,1)=0.
      PP(I,2)=1./XA(I,2)
      QQ(I,2)=GEV(I,2)/XA(I,2)
      PP(I,3)=0.
      QQ(I,3)=GEV(I,3)/XA(I,3)
      ELSE
C  *** ERECTOPHILE LAYER ***
      DELRN(I,1)=WU(I)*DRN(I)/2.
      DELRN(I,2)=(1-WU(I))*DRN(I)/2.
      DELRN(I,3)=WL(I)*DRN(I)/2.
      DELRN(I,4)=(1-WL(I))*DRN(I)/2.
      GEC(I,1)=GBW(I)*WU(I)*DLAI(I)
      GEC(I,2)=GBD(I)*(1-WU(I))*DLAI(I)
      GEC(I,3)=GBW(I)*WL(I)*DLAI(I)
      GEC(I,4)=GBD(I)*(1-WL(I))*DLAI(I)
      GEV(I,1)=GEC(I,1)
      GEV(I,2)=GBD(I)*GSU(I)/(GBD(I)+GSU(I))
      GEV(I,2)=GEV(I,2)*(1-WU(I))*DLAI(I)
      GEV(I,3)=GEC(I,3)
      GEV(I,4)=GBD(I)*GSL(I)/(GBD(I)+GSL(I))
      GEV(I,4)=GEV(I,4)*(1-WL(I))*DLAI(I)
      DO 12 J=1,4
   12 XA(I,J)=GEC(I,J)+(DEL/GAM)*GEV(I,J)
```

```
      IF(WU(I))14,14,13
   13 DDU(I)=XA(I,1)*XA(I,2)+(XKU(I)/RCP)*(XA(I,1)+XA(I,2))
      PP(I,1)=(WU(I)*XA(I,2)/2.+XKU(I)/RCP)/DDU(I)
      PP(I,2)=((1-WU(I))*XA(I,1)/2.+XKU(I)/RCP)/DDU(I)
      GVU=(GEV(I,1)+GEV(I,2))*XKU(I)/RCP
      QQ(I,1)=(XA(I,2)*GEV(I,1)+GVU)/DDU(I)
      QQ(I,2)=(XA(I,1)*GEV(I,2)+GVU)/DDU(I)
      GO TO 15
   14 PP(I,1)=Ø.
      QQ(I,1)=Ø.
      PP(I,2)=1./2./XA(I,2)
      QQ(I,2)=GEV(I,2)/XA(I,2)
   15 IF(WL(I))17,17,16
   16 DDL(I)=XA(I,3)*XA(I,4)+(XKL(I)/RCP)*(XA(I,3)+XA(I,4))
      PP(I,3)=(WL(I)*XA(I,4)/2.+XKL(I)/RCP)/DDL(I)
      PP(I,4)=((1-WL(I))*XA(I,3)/2.+XKL(I)/RCP)/DDL(I)
      GVL=(GEV(I,3)+GEV(I,4))*XKL(I)/RCP
      QQ(I,3)=(XA(I,4)*GEV(I,3)+GVL)/DDL(I)
      QQ(I,4)=(XA(I,3)*GEV(I,4)+GVL)/DDL(I)
      GO TO 2Ø
   17 PP(I,3)=Ø.
      QQ(I,3)=Ø.
      PP(I,4)=1./2./XA(I,4)
      QQ(I,4)=GEV(I,4)/XA(I,4)
   2Ø END IF
C  ***  RECURRENT RELATIONS  ***
      MUV(I)=Ø.
      PI(I)=Ø.
      JF=NSL(I)
      DO 22 J=1,JF
      MUV(I)=MUV(I)+GEV(I,J)*PP(I,J)
   22 PI(I)=PI(I)+GEC(I,J)*QQ(I,J)
      SIG1=Ø.
      SIG2=Ø.
      SIG3=Ø.
      B(1)=Ø.
      DO 3Ø I=1,NL
      JF=NSL(I)
      DO 25 J=1,JF
      CC(I,J)=-GEC(I,J)/GA(I)
      CV(I,J)=-GEV(I,J)/GA(I)
      SIG1=SIG1+CV(I,J)
      SIG2=SIG2+(CV(I,J)-CC(I,J))*QQ(I,J)
      SIG3=SIG3+(CC(I,J)-CV(I,J))*PP(I,J)
      C(I)=DEL*SIG3
      IF(I.EQ.1) GO TO 25
      B(I)=-GA(I-1)/GA(I)
   25 A(I)=1-B(I)-SIG1+(DEL/GAM)*SIG2
   3Ø CONTINUE
      BE(1)=Ø.
      BE(2)=1.
      EP(1,1)=DEL*MUV(1)/PI(1)
```

```
      EP(2,1)=C(1)
      EP(2,2)=DEL*MUV(2)/PI(2)
      DO 50 I=2,NL
      AL(I+1)=A(I)*AL(I)+B(I)*AL(I-1)
      BE(I+1)=A(I)*BE(I)+B(I)*BE(I-1)
      EP(I+1,I-1)=A(I)*C(I-1)
      EP(I+1,I)=C(I)
      EP(I+1,I+1)=DEL*MUV(I+1)/PI(I+1)
      DO 50 J=1,I-2
   50 EP(I+1,J)=A(I)*EP(I,J)+B(I)*EP(I-1,J)
C  ***  TOTAL FLUXES CALCULATION  ***
      SIGA=0.
      SIGB=0.
      SER=0.
      DO 60 I=1,NN
      SIGE(I)=0.
      SIGA=SIGA+PI(I)*AL(I)/GA0
      SIGB=SIGB+PI(I)*BE(I)/GA(1)
      DO 55 K=I,NN
   55 SIGE(I)=SIGE(I)+PI(K)*EP(K,I)
   60 SER=SER+SIGE(I)*DRN(I)
      LE0=DEL*(SIGA+SIGB)*(RN0-S)+SER+RCP*GA0*SIGA*DA0
      LE0=LE0/(GAM+(DEL+GAM)*(SIGA+SIGB))
      C0=RN0-S-LE0
C  ***  MICROCLIMATIC PROFILES CALCULATION  ***
      CI=C0
      LEI=LE0
      TI=TA0+C0/RCP/GA0
      EI=EA0+LE0*GAM/RCP/GA0
      DO 80 I=1,NN
      SIGDC=0.
      SIGDLE=0.
      TA(I)=TI
      EA(I)=EI
      IF(EA(I).GT.ES(TA(I))) EA(I)=ES(TA(I))
      HR(I)=EA(I)/ES(TA(I))*100
      DA(I)=ES(TA(I))-EA(I)
      JF=NSL(I)
      DO 65 J=1,JF
      TET=PP(I,J)*DRN(I)/RCP-QQ(I,J)*DA(I)/GAM
      TL(I,J)=TET+TI
      DC(I,J)=RCP*GEC(I,J)*TET
      DLE(I,J)=(RCP/GAM)*GEV(I,J)*(DEL*TET+DA(I))
      SIGDC=SIGDC+DC(I,J)
   65 SIGDLE=SIGDLE+DLE(I,J)
      IF(I.EQ.NN) GO TO 67
      CI=CI-SIGDC
      LEI=LEI-SIGDLE
      TI=TI+CI/RCP/GA(I)
      EI=EI+LEI*GAM/RCP/GA(I)
   67 QIU=DLE(I,1)*TISTEP*60/LAM/1000
      VU2=VU(I)-QIU
      IF(VU2)70,70,72
   70 VU(I)=.0
```

```
      WU(I)=.0
      IF(WDU(I).EQ.0) WDU(I)=NSTEP*TISTEP/60.
      GO TO 75
   72 WU(I)=WU(I)*(VU2/VU(I))**AAB
      VU(I)=VU2
      WU(I)=100.*WU(I)
   75 IF(JF.NE.4) GO TO 80
      QIL=DLE(I,3)*TISTEP*60/LAM/1000
      VL2=VL(I)-QIL
      IF(VL2)76,76,77
   76 VL(I)=0.
      WL(I)=0.
      IF(WDL(I).EQ.0) WDL(I)=NSTEP*TISTEP/60.
      GO TO 80
   77 WL(I)=WL(I)*(VL2/VL(I))**AAB
      VL(I)=VL2
      WL(I)=100.*WL(I)
   80 CONTINUE
      WRITE(9,*)
      WRITE(9,110)NSTEP
      WRITE(9,*)
C  ***  RN0  NET RADIATION (W/m2)  ***
C  ***  S    SOIL HEAT FLUX (W/m2) ***
C  ***  C0   SENSIBLE HEAT FLUX (W/m2) ***
C  ***  LE0  LATENT HEAT FLUX (W/m2) ***
C  ***  U()  WIND VELOCITY PROFILE (m/s) ***
C  ***  TA() AIR TEMPERATURE PROFILE (C) ***
C  ***  HR() AIR HUMIDITY PROFILE (%) ***
C  ***  RSL() LOWER STOMATAL RESISTANCE PROFILE (s/m) ***
C  ***  TL(,J) LEAF TEMPERATURE PROFILE (C)  ***
C  ***         J: NUMBER OF THE SUBLAYER  ***
C  ***  WDU() WETNESS DURATION PROFILE ON THE UPPER SIDE
(mn)
C  ***  WDL() WETNESS DURATION PROFILE ON THE LOWER SIDE
(mn)
      WRITE(9,120)
      WRITE(9,*)RN0,S,C0,LE0
      WRITE(9,130)
      WRITE(9,*)(U(I),I=1,NL)
      WRITE(9,135)
      WRITE(9,*)(RSL(I),I=1,NL)
      WRITE(9,140)
      WRITE(9,*)(TA(I),I=1,NL)
      WRITE(9,150)
      WRITE(9,*)(HR(I),I=1,NL)
      WRITE(9,160)
      WRITE(9,*)(VU(I),I=1,NN)
      WRITE(9,*)
      WRITE(9,*)(VL(I),I=1,NL)
      WRITE(9,170)
      WRITE(9,*)(WU(I),I=1,NN)
      WRITE(9,*)
      WRITE(9,*)(WL(I),I=1,NL)
      WRITE(9,180)
```

```
      WRITE(9,*)(TL(I,1),I=1,NN)
      WRITE(9,*)(TL(I,2),I=1,NN)
      WRITE(9,*)
      WRITE(9,*)(TL(I,3),I=1,NL)
      WRITE(9,*)(TL(I,4),I=1,NL)
      WRITE(9,*)
  110 FORMAT(1X,'TIME STEP=',I3)
  120 FORMAT(1X,'ENERGY BALANCE:RN0,S,C0,LE0')
  130 FORMAT(1X,'WIND PROFILE')
  135 FORMAT(1X,'LOWER STOMATAL RESISTANCE PROFILE')
  140 FORMAT(1X,'AIR TEMPERATURE PROFILE')
  150 FORMAT(1X,'HUMIDITY PROFILE')
  160 FORMAT(1X,'INTERCEPTION PROFILE')
  170 FORMAT(1X,'WET SURFACE PROFILE')
  180 FORMAT(1X,'SURFACE TEMPERATURE PROFILE')
  190 FORMAT(1X,'WETNESS DURATION PROFILE')
      GO TO 2
   99 WRITE(9,190)
      WRITE(9,*)(WDU(I),I=1,NL)
      WRITE(9,*)
      WRITE(9,*)(WDL(I),I=1,NL)
      STOP
      END
C
************************************************************
C  ***  SUBROUTINES  ***
C
************************************************************
      SUBROUTINE RAD(RG,DRN,S,NL,RG0,RN0,DLAI,ALN,ALG,COE)
C  ***  CALCULATE THE PROFILES OF NET AND GLOBAL RADIATION
C  ***                 AND THE SOIL HEAT FLUX
      DIMENSION RG(10),DRN(10),DLAI(10)
      NN=NL+1
      SIGDRN=0.
      DO 20 I=1,NL
      I1=I-1
      SLAI=0.
      IF(I1)15,15,5
    5 DO 10 J=1,I1
   10 SLAI=SLAI+DLAI(J)
   15 DRN(I)=RN0*EXP(-ALN*SLAI)*(1-EXP(-ALN*DLAI(I)))
      SIGDRN=SIGDRN+DRN(I)
   20 RG(I)=RG0*EXP(-ALG*SLAI)
      DRN(NN)=(RN0-SIGDRN)*(1.-COE)
      S=(RN0-SIGDRN)*COE
      RETURN
      END
C
************************************************************
      SUBROUTINE AEREO(GA0,UZH,EDZH,U0,ZR,ZH)
C  ***  CALCULATE THE AERODYNAMIC CHARACTERISTICS OF THE
C  ***                       CANOPY
      ZD=.75*ZH
      Z0=.13*ZH
```

```
      UST=.4*U0/ALOG((ZR-ZD)/Z0)
      UZH=UST*ALOG((ZH-ZD)/Z0)/.4
      EDZH=.4*UST*(ZH-ZD)
      GA0=.4*UST/ALOG((ZR-ZD)/(ZH-ZD))
      RETURN
      END
C
************************************************************
      SUBROUTINE WIND(U,GA,DZ,NL,ZH,UZH,EDZH,ALU,ALK)
C  ***  CALCULATE THE WIND PROFILE AND THE AERODYNAMIC
C  ***               CONDUCTANCE PROFILE
      DIMENSION U(10),GA(10),DZ(10)
      DO 20 I=1,NL
      IF(I.EQ.1) THEN
      ZZ=ZH-DZ(I)/2.
      ELSE
      ZZ=ZZ-(DZ(I-1)+DZ(I))/2.
      END IF
      U(I)=UZH/EXP(ALU*(1-ZZ/ZH))
      ED=EDZH/EXP(ALK*(1-ZZ/ZH))
   20 GA(I)=ED/DZ(I)
      RETURN
      END
C
************************************************************
      SUBROUTINE BOLA(U,GBD,GBW,NL,AAD,AAW,CW)
C  ***  CALCULATE THE BOUNDARY-LAYER CONDUCTANCE PROFILES  *
      DIMENSION U(10),GBD(10),GBW(10)
      DO 10 I=1,NL
      GBD(I)=AAD*(U(I)/CW)**.5
   10 GBW(I)=AAW*(U(I)/CW)**.5
      RETURN
      END
C
************************************************************
      SUBROUTINE STOMA(GSU,GSL,RG,NL,GSN,GSX,RGN,RGX,GSUP)
C  ***  CALCULATE THE STOMATAL CONDUCTANCE PROFILE  ***
      DIMENSION GSU(10),GSL(10),RG(10)
      DO 10 I=1,NL
      GSU(I)=GSUP
      Y=(RG(I)-RGN)/(RGX-RGN)
      IF(Y.GT.1.)Y=1.
      IF(Y.LT.0.)Y=0.
   10 GSL(I)=GSN+(GSX-GSN)*Y
      RETURN
      END
C
************************************************************
      FUNCTION ES(X)
C  ***  CALCULATE THE SATURATED VAPOUR PRESSURE  ***
      ES=611*EXP(17.25*X/(237.3+X))
      RETURN
      END
************************************************************
```

VI.CONCLUSION

In the present document we give the equations and algorithms needed to calculate the energy exchanges of a plant canopy in partially wet conditions. These new equations offer explicit expressions of total fluxes of sensible and latent heat above the canopy, which can be put in the form of the familiar Penman's formulae. This new set of equations simplifies the resolution of the basic equations of multi-layer models in partially wet conditions. They allow one to simulate the entire microclimate of a partially wet canopy and to predict more readily the duration of persistence of surface water on leaves after rain or dew deposit. Moreover the model is easy to program because it is essentially based upon explicit expressions and recursive relations.

This model was tested using experimental data obtained on a field bean crop in the Paris area (Lhomme and Huber, 1990). Now it has to be calibrated and tested on a plantain or banana canopy. It is what we are carrying out in La Lola experimental station.

LIST OF SYMBOLS

C	sensible heat flux density in vertical direction (Wm^{-2})
λE	latent heat flux density in vertical direction (Wm^{-2})
c_p	specific heat of air at constant pressure ($Jkg^{-1}K^{-1}$)
D_a	saturation deficit of air (Pa)
e_a	water vapour pressure of air (Pa)
$e_s(T)$	saturated vapour pressure at temperature T (Pa)
ga	aerodynamic conductance (ms^{-1})
gb	boundary-layer conductance (ms^{-1})
gs	stomatal conductance (ms^{-1})
ge_c	equivalent conductance for horizontal heat transfer (ms^{-1})
ge_v	equivalent conductance for horizontral vapour transfer (ms^{-1})
$J\phi$	defined by Equation (B.61) (Wm^{-2})
$k_{u,i}$	coefficient for heat conduction between dry and wet parts of the upper side of the leaves in layer i ($Wm^{-2}K^{-1}$)
$k_{l,i}$	idem for the lower side
K	eddy diffusivity for sensible and latent heat (m^2s^{-1})
LAI	leaf area index (m^2m^{-2})
m	number of sub-layers
n	number of layers
Rn	net radiation flux density (Wm^{-2})
S	soil heat flux density (Wm^{-2})
T	temperature (°C)
W	relative surface of free water on the leaves (%)
β	resorption coefficient defined by Equation (C.18)
γ	psychrometric constant ($66Pa°C^{-1}$)
Δ	slope of the saturated vapour pressure curve ($Pa°C^{-1}$)
δz_i	thickness of layer i (m)
δLAI_i	leaf area index of layer i (m^2m^{-2})
$\delta Rn_{i,j}$	net radiation flux density absorbed by sub-layer j of layer i (Wm^{-2})
$\delta C_{i,j}$	sensible heat flux density emanating from sub-layer j of layer i (Wm^{-2})
$\delta\lambda E_{i,j}$	latent heat flux density emanating from sub-layer j of layer i (Wm^{-2})
ρ	air density (kgm^{-3})
η	effective conduction coefficient defined by Equation (C.14)
Φ_i	conduction heat flux density between dry and wet parts of layer i (Wm^{-2})
$\theta_{i,j}$	defined by Equation (B.3)

Subscripts

a	for air
L	for leaves
n	for soil surface
c	for sensible heat
v	for latent heat
i	for layers
j	for sub-layers
Ø	for above canopy parameters
u	for the upper side of leaves
l	for the lower side of leaves

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