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Effects of leaf area profiles and canopy stratification on simulated energy fluxes: the problem of vertical spatial scale

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Abstract

We investigated the effects of the shape of leaf area profiles and the number of canopy layers on simulated sensible and latent heat fluxes using a gradient diffusion-based biometeorological model. Three research questions were addressed through simulation experiments: (1) Given the same amount of cumulative leaf area in the vertical direction, how does the shape of the leaf area profile affect simulation results? (2) For a given leaf area profile, how does the number of layers influence the simulation results? (3) How do these two factors interact with each other in affecting the simulated energy fluxes? Our results demonstrated that the scheme of canopy stratification could substantially affect the simulated energy fluxes, and that the effect exhibited a consistent pattern — an S-shaped response curve. There existed a minimal number of layers for achieving a required degree of accuracy. The turning point of the S-shaped curve represented the optimal number of layers, indicating a desirable balance between the accuracy of the model and demands for computation and data collection. Our results also showed that differences in the shape of leaf area profiles alone could significantly alter the simulated energy fluxes even if the total amount of leaves in the canopy and the values of all other model parameters remained the same. Furthermore, the shape of leaf area profiles interacted with the number of layers in affecting the simulated energy fluxes. While considerable impacts were observed for all leaf area profiles, complex (nonlinear) shapes exacerbated the effects of changing the number of layers.

Keywords: Canopy structure; Latent heat flux; Leaf area index; Micrometeorology; Number of layers; Scale; Sensible heat flux

1. Introduction

Spatial patchiness is ubiquitous in ecological systems and has various effects on system function and dynamics (Levin et al., 1993; Wu and Levin, 1994, 1997; Wu and Loucks, 1995). The horizontal patchiness in space has attracted a great deal of attention from ecologists, and become a central theme in the field of landscape ecology (Turner, 1989; Pickett and Cadenasso, 1995; Wu and Loucks, 1995; Reynolds and Wu, 1999). Recent studies have shown that spatial

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patchiness may have significant effects on the flows of organisms, energy, and materials in a landscape. Importantly, the quantification of spatial patchiness and the determination of its effects on ecological processes seem highly dependent upon the scale of observation (e.g. Turner et al., 1989; Baldocchi, 1993; Qi and Wu, 1996). The effects of scale on the results of statistical analysis based on area-based data has long been known in both geography and ecology (e.g. gerrymandering, the modifiable areal unit problem or MAUP, problems of sample size and position; see Wu and Jelinski, 1995; Jelinski and Wu, 1996 for reviews). Ecologists are also acutely aware of the existence of vertical heterogeneity in vegetation structure in relation to the distribution of energy and resources (e.g. light, moisture, CO_2) and biological activities (e.g. photosynthesis, plant competition for light). How does the vertical canopy structure affect ecological processes? How does the scale of observation or measurement (i.e. sampling intervals or extent in space or time) influence the pattern-process interactions? While ecologists become acutely aware of the problems associated with scale, studies are still lacking to effectively address these questions.

Biometeorological or micrometeorological models are usually developed for understanding and predicting the energy and material exchanges between vegetation and atmosphere, or through the soil-plant-atmosphere continuum (Cowan, 1968; Waggoner, 1975; Goudriaan, 1977; Brutsaert, 1982; Halldin and Lindroth, 1986; Wu, 1990; Raupach, 1991). To deal with the vertical heterogeneity in vegetation structure, a common approach these models employ is to stratify the canopy into multiple layers and simulate energy and mass fluxes across these layers by coupling the relevant processes. These models provide excellent examples for studying the interactions between vertical vegetation patchiness (e.g. the distribution of leaf area density) and ecological processes using a largely physics-based, mechanistic approach. Nevertheless, the selection of the number of layers within the canopy usually is arbitrary, and systematic studies of how the scheme of stratifying the canopy and the characteristics of the leaf area density profile affect the outcome of such models are rare (Paw U, personal comm.).

Thus, the main purpose of this study was to help understand the effects of canopy structure on simulated energy exchange processes in particular and the problem of vertical spatial scale in general. Specifically, we investigated the effects of varying the profile of leaf area density and the number of canopy layers on the simulated sensible and latent heat fluxes by conducting a series of simulation experiments using a multiple-layer micrometeorological model. Three specific research questions were directly addressed here: (1) Given the same amount of cumulative leaf area in the vertical direction, how does the shape of the leaf area density profile affect simulation results? (2) For a given leaf area density profile, how does the number of layers influence the simulation results? (3) How do these two factors interact with each other?

There exist two general types of micrometeorological models. The gradient-diffusion models use a ‘first-order’ closure approach and flux-gradient profile relationships for finding a unique convergent solution for the system of equations, and represent a well-developed approach. Because the gradient-diffusion theory (K-theory) can not account for possible counter-gradient transport and because the scale length of turbulent eddies may change substantially within plant communities, these models can become problematic. The second type of micrometeorological models uses a higher- (second and third-) order closure scheme for modeling the turbulent transfer processes of plant communities (e.g., Wilson and Shaw, 1977; Paw U, 1989). Higher-order closure models overcome the deficiencies of the gradient-diffusion approach and usually are more accurate, but they have much higher data and computational demands. Because the purpose of this study was not to develop a more accurate micrometeorological model, but to focus on the effects of the vertical distribution of leaf area and canopy stratification, we chose to use a K-theory based model that was validated previously against field data (Wu, 1990).

In the following, we shall first describe the simulation model and the design of simulation experiments, then present the results, and finally conclude the paper with major findings and discussion.

2. Model description

The micrometeorological model we used for this study was the plant-atmosphere-soil simulation model (PASSM) developed by Wu (1990). Because the model was documented in detail previously, here we only provide a succinct description of the model structure and its major components.

PASSM is a steady-state, multiple-layered, vegetation-atmosphere interaction model based on the gradient-diffusion theory. Although all energy and mass exchange processes within and above plant communities are essentially three-dimensional in nature, they have been studied widely and effectively by using a one-dimensional approach in which the flows and canopy properties are horizontally averaged (Monteith, 1973; Raupach and Thom, 1981; Brutsaert, 1982; Halldin and Lindroth, 1986). According to the gradient-diffusion theory, the vertical flux density of a certain property is proportional to the product of turbulent diffusivity and the concentration gradient of the property, that is,

$$Q_C = -\rho K_C \frac{dC}{dz} \quad (1)$$

where Q_C is the vertical flux density of a property (usually in W m^{-2}), C is the mean concentration of the entity (kg m^{-3}), ρ is the air density, and K_C is the diffusivity for that property (m^2 s^{-1}). For sensible and latent heat fluxes, Eq. 1 becomes

$$SH = -\rho C_p K_h \frac{dT_A}{dz} \quad (2)$$

and

$$LE = -\rho L_t K_w \frac{dQ_A}{dz} \quad (3)$$

where SH and LE are the sensible and latent heat flux densities, C_p is the specific heat of air, L_t is the latent heat for vaporization of water, K_h and K_w are the turbulent diffusivities for sensible heat and water vapor, T_A and Q_A are air temperature and humidity, and z is the height.

PASSM has three major components: energy balance in the plant community, radiation distribution, and momentum, heat, and water exchange processes. Table 1 lists the main equations for modeling these distinct, but interrelated processes. The names and meanings of symbols in the equations are summarized in Table 2. Here we shall only briefly describe several governing equations that capture the essence of the model.

Energy balance within a plant community can be described as

$$R_N = SH + LE + G \quad (4)$$

where R_N is the total net radiation, SH and LE are the sensible and latent heat flux densities, and G is the soil heat flux density. The distribution of radiation within a plant community is modelled using the exponential equation:

$$S_T(z) = S_{TCH}\ \exp[-\alpha_L CLAI(z)] \quad (5)$$

where $S_T(z)$ is the total solar radiation, S_{TCH} is the total solar radiation at the canopy height, α_L is the radiation extinction coefficient by leaves, and CLAI is the downward cumulative leaf area index. Equations for shortwave and longwave rediation transfer within a plant community are given in Table 1. The momentum transfer can be described by the following equations:

$$\frac{dU}{dz} = \frac{U^*}{k(z-d)}\ \Phi_m(\Gamma) \ \text{for}\ z \geq z_{CH} \quad (6)$$

$$\frac{dU}{dz} = \frac{\alpha_w U(z_{CH})}{z_{CH}}\ e\alpha_w\left(\frac{z}{z_{CH}} - 1\right) \ \text{for}\ z < z_{CH} \quad (7)$$

where U is the wind speed at height z, U^* is the friction velocity, z_{CH} is the average canopy height, k is Von Karman's constant, d is the zero plane displacement height, $\Phi_m(\Gamma)$ is the stability function for momentum, and α_W is the extinction coefficient for wind velocity. The sensible and latent heat transfer within the plant community is modelled by the following set of differential equations:

$$\frac{dSH}{dz} = \frac{\rho C_p(T_L(z) - T_A(z))\text{LAD}(z)}{R_h(z)} \quad (8)$$

Table 1
List of equations in PASSM[a]

Equation	Description
Energy balance within plant communities	
$R_N = SH + LE + G$	General equation for energy balance in plant communities
$\frac{dSH}{dz} = \frac{\rho C_p (T_L(z) - T_A(z))\text{LAD}(z)}{R_h(z)}$	Vertical divergence equation of sensible heat flux density
$\frac{dLE}{dz} = \frac{\rho L_t (Q_L(z) - T_A(z))\text{LAD}(z)}{R_w(z) + R_s(z)}$	Vertical divergence equation of latent heat flux density
$\frac{dR_N}{dz} = \frac{2\rho C_p \text{LAD}(z)}{R_h(z)} (T_L(z) - T_A(z)) + \frac{2\rho L_t \text{LAD}(z)}{R_w(z) + R_s(z)} (Q_L(z) - Q_A(z))$	Vertical divergence equation of energy balance
Radiation distribution within plant communities	
$R_N(z) = S_N(z) + L_N(z)$	Total net radiation flux density
$S_N(z) = a_L S_T(z)$	Absorbed shortwave radiation flux density
$S_T(z) = S_{TCH} \exp[-\alpha_L \text{CLAI}(z)]$	Total shortwave radiation flux density
$L_N(z) = V(z, S_{KY})\delta(T_G^4 - T_L(z)^4) + V(z, G_{RD})\delta(T_G^4 - T_L(z)^4)$ $+ \Sigma V(z, X)\delta(T_L(X)^4 - T_L(z)^4)$	Total net longwave radiation flux density
Momentum, heat, and water exchange processes	
$U(z) = \frac{U^*}{k} \ln \frac{z-d}{z_0}$	Wind speed profile above plant communities for the neutral atmosphere condition
$U(z_2) - U(z_1) = \frac{U^*}{k} [\ln \frac{z_2 - d}{z_1 - d} - \Phi_{m2}(\Gamma) + \Phi_{m1}(\Gamma)]$	Wind speed profile above plant communities for the stable and unstable atmosphere conditions
$U^* = \frac{kU(z_{RH})}{\ln[z_{RH} - d)/z_0] - \Phi_m(\Gamma_{RH})}$	Friction velocity or eddy velocity
$\Phi_h(\Gamma) = \Phi_w(\Gamma) = \Phi_m(\Gamma) = 1.0$ (Neutral condition) $\Phi_h(\Gamma) = \Phi_w(\Gamma) = \Phi_m^2(\Gamma) = (1 - 16\Gamma)^{-1/2}$ (Unstable condition) $\Phi_h(\Gamma) = \Phi_w(\Gamma) = \Phi_m(\Gamma) = 1 + 5\Gamma$ (Stable condition)	Stability functions for heat (Φ_h), water vopor (Φ_w), and moment (Φ_m) for different atmosphere conditions
$\Gamma = \frac{z-d}{L_{mo}}$	Stability parameter
$L_{mo} = \frac{\rho C_p T_A(z) U^*}{kgSH}$	Monin–Obukhov length
$U(z) = U(z_{CH})\exp[\alpha_w(z/z_{CH} - 1)]$	Wind speed profile within plant communities
$T_{A1} = T_{A2} + \frac{SH}{\rho C_p k U^*}\left[\ln \frac{z_2 - d}{z_1 - d} - \Phi_h(\Gamma_2) + \Phi_h(\Gamma_1)\right]$	Air temperature profile above plant communities
$Q_{A1} = Q_{A2} + \frac{LE}{\rho L_t k U^*}\left[\ln \frac{z_2 - d}{z_1 - d} - Q_w(\Gamma_2) + \Phi_w(\Gamma_1)\right]$	Air specific humidity profile above plant communities
$T_A(z) = T_L(z) - \frac{R_h(z)}{\rho C_p \text{LAD}(z)} \frac{dSH}{dz}$	Air temperature profile within plant communities
$Q_A(z) = Q_L(z) - \frac{R_w(z) + R_s(z)}{\rho L_t \text{LAD(z)}} \frac{dLE}{dz}$	Air specific humidity profile within plant communities
$T_L(z) = T_A(z) + \frac{R_h(z)}{2\rho C_p} R_N(z) - \frac{L_t R_h(z)(Q_L(z) - Q_A(z))}{C_p(R_w(z) + R_s(z))}$	Leaf temperature profile
$k_h(z) = \frac{kU^*(z-d)}{\phi_h}$	Eddy diffusivity for heat transfer above plant communities
$K_w(z) = \frac{kU^*(z-d)}{\phi_w}$	Eddy diffusivity for water vapor transfer above plant communities
$K_x(z) = K_{xCH} \exp(\alpha_K(z/z_{CH} - 1))$	Eddy diffusivity for heat ($x = h$) and water vapor ($x = w$) within plant communities

[a] The model contains three major components: energy balance in plant communities, radiation distribution, and momentum, heat and water exchange processes (Wu 1987, 1990). See Table 2 for the name and meaning of each symbol.

Table 2
Variables and parameters in PASSM

Symbol	Variables and definitions	Units
a_L	Leaf absorptivity for solar radiation	dimensionless
A	Area density of plant elements	$m^2\ m^{-3}$
CLAI	Downward cumulative leaf area index	$m^2\ m^{-2}$
C_p	Specific heat of air: 1000.0	$J\ kg^{-1}\ °C^{-1}$
d	Zero plane displacement height	m
D_L	Average dimension of leaves	m
g	Acceleration of gravity: 9.81	$m\ s^{-1}$
G	Soil heat flux density	$W\ m^{-2}$
k	Von karman's constant: 0.40	dimensionless
K_h	Turbulent diffusivity for sensible heat	$m^2\ s^{-1}$
K_w	Turbulent diffusivity for water vapor	$m^2\ s^{-1}$
LAD	Leaf area density	$m^2\ m^{-3}$
LE	Latent heat flux density	$W\ m^{-2}$
L_I	Incoming longwave radiation	$W\ m^{-2}$
L_{mo}	Monin–Obukhov length	m
L_N	Net longwave radiation flux density	$W\ m^{-2}$
L_t	Latent heat of vaporization of water	$J\ kg^{-1}$
Q_A	Specific humidity of air	$kg\ kg^{-1}$
Q_L	Specific humidity of leaves	$kg\ kg^{-1}$
R_h	Leaf boundary-layer resistance for sensible heat transfer	$s\ m^{-1}$
R_N	Total net radiation	$W\ m^{-2}$
R_s	Stomatal resistance for water vapor	$s\ m^{-1}$
R_w	Leaf boundary-layer resistance for latent heat transfer	$s\ m^{-1}$
SH	Sensible heat flux density	$W\ m^{-2}$
S_N	Net solar radiation flux density	$W\ m^{-2}$
S_T	Total solar radiation	$W\ m^{-2}$
T_A	Actual air temperature	°C
T_G	Soil surface temperature	°C
T_L	Leaf temperature	°C
T_{SK}	Apparent sky temperature	°C
U	Wind velocity	$m\ s^{-1}$
U^*	Friction velocity	$m\ s^{-1}$
V	View factor	dimensionless
z	Vertical distance from the soil surface	m
z_o	Roughness length	m
z_{CH}	Average height of a plant community	m
α_K	Radiation extinction coefficient for eddy diffusivity	dimensionless
α_L	Radiation extinction coefficient by leaves	dimensionless
α_W	Extinction coefficient for wind velocity	dimensionless
Γ	Stability parameter, defined by $(z-d)/L_{mo}$	
ρ	Air density	$kg\ m^{-3}$
σ	Stefan-Boltzmann constant: 5.57×10^{-8}	$W\ m^{-2}\ k^{-4}$
ϕ_h	Stability function for heat	
ϕ_m	Stability function for momentum	
ϕ_w	Stability function for water vapor	
Φ_h	Integrated stability parameter for heat	
Φ_m	Integrated stability parameter for momentum	
Φ_w	Integrated stability parameter for water vapor	
Subscripts		
m	Momentum	
h	Sensible heat	
w	Water vapor	
A	Air	
L	Leaf	
CH	Plant community height	
RH	Reference height	
N	Net	

$$6\frac{dLE}{dz} = \frac{\rho L_t(Q_L(z) - Q_A(z))\mathrm{LAD}(z)}{R_w(z) + R_s(z)} \quad (9)$$

where ρ is air density, C_p is the specific heat of air, T_L and T_A are the leaf and air temperature, Q_L and Q_A are the leaf and air specific humidity, LAD(z) is the leaf area density at height z, R_w is the leaf boundary-layer resistance for latent heat transfer, and R_s is the stomatal resistance for water vapor.

The input data for PASSM include upper boundary conditions (radiation, air temperature, specific humidity, and wind speed at the reference height above the canopy), lower boundary conditions (temperature and specific humidity at the soil surface), and plant community characteristics (downward cumulative leaf area index or leaf area density profile, average dimension of leaves, and average canopy height). The default number of canopy layers in PASSM is 20, with the reference height (z_{RH}) being twice of the canopy height (z_{CH}). The simulation of the model is carried out

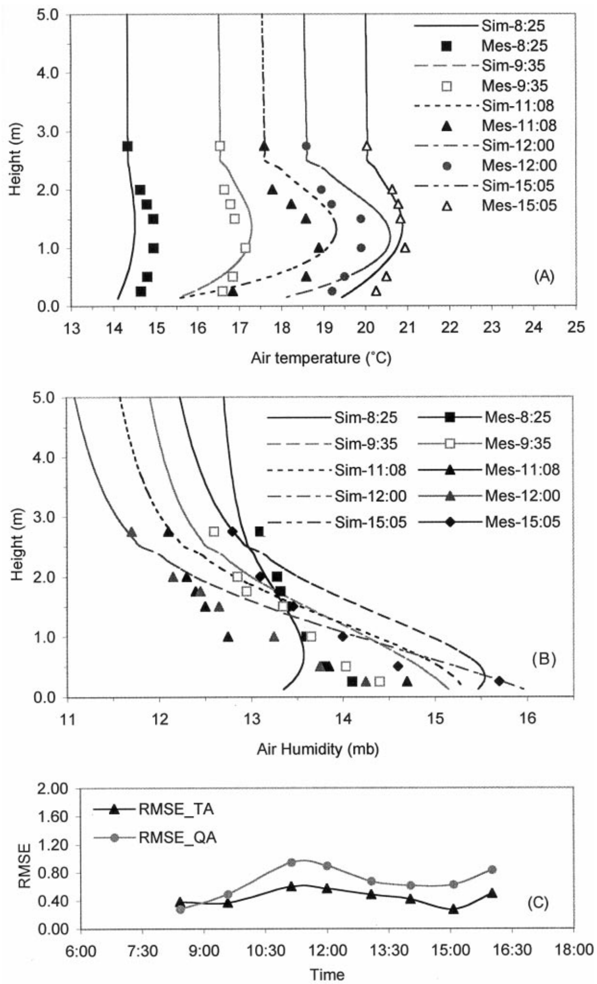

Fig. 1. Simulated and measured air temperature and humidity profiles for a cornfield (BC field): (A) air temperature profile, (B) air humidity profile, and (C) root mean square error (RMSE*) of predicted air temperature and humidity profiles. RMSE varied for different time periods, but was always smaller than 1°C for temperature and 1 mb for humidity. Measurements were made on September 12, 1962 (Brown and Covey, 1966). $*RMSE = \sqrt{\Sigma_{i=1}^{n}(X_{\mathrm{mod}} - X_{msd})_i^2/n}$, where X_{mod} is the model prediction and X_{msd} is the measured value.

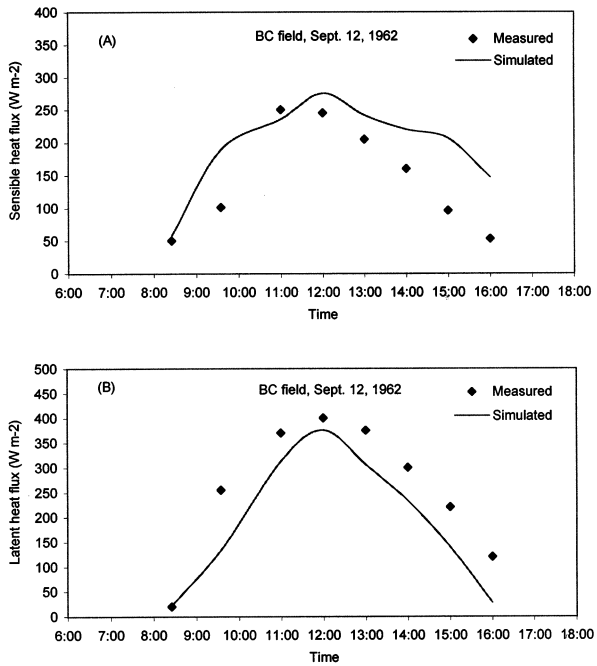

Fig. 2. Simulated and measured heat fluxes for a cornfield (BC field) at different times during a day: (A) sensible heat flux, and (B) latent heat flux. Measurements were made on September 12, 1962 (Brown and Covey, 1966).

by coupling equations describing energy balance, radiation distribution, and transfer processes for momentum, heat, and water vapor. A unique convergent solution for the systems of equations is achieved through iterations of successive approximations (Wu, 1990).

The original version of PASSM (Wu, 1990) was validated against field measurements published by Brown and Covey (1966; BC field hereafter) and Stewart and Lemon (1969); SL field hereafter). Since we modified the Fortran code substantially to address the research questions in this study, we revalidated the model using the same field data sets before carrying out the simulation experiments. The results showed that the model simulated air temperature and humidity profiles fairly well (Fig. 1A, B), with root mean square error (RMSE) smaller than 1°C or 1 mb for all simulation time periods (Fig. 1C), and that simulated and measured sensible and latent heat fluxes agreed reasonably well (Fig. 2).

3. Simulation experiment design

To investigate how the vertical canopy structure and stratification scheme affect the accuracy of the multiple-layer micrometeorological simulation model, we focused on three groups of variables: (1) the cumulative leaf area index, CLAI(z), and leaf area density, LAD(z); (2) the number of layers into which the plant community is stratified; and (3) the output sensible and latent heat fluxes. The first two groups of variables can be perceived as independent variables whereas the third group as dependent variables. 3 depicts the conceptual framework and major research step in this study. In a series of simulation experiments, we manipulated the leaf area profiles and the number of layers, with all other model parameters and input data kept constant. This was necessary to make sure that the variations between model runs were due only to the changes of the first two groups of variables.

To address our research question regarding the effects of varying canopy structure, we used seven different cumulative leaf area index profiles, CLAI(z), corresponding to seven leaf area density profiles, LAD(z) (Fig. 4). CLAI(z) and LAD(z) are related by the following equations:

$$\mathrm{CLAI}(z) = \int_{Z}^{ZCH} \mathrm{LAD}(z)dz \quad (10)$$

or

$$\mathrm{LAD}(z) = \frac{\mathrm{d}(\mathrm{CLAI}(z))}{\mathrm{d}z} \quad (11)$$

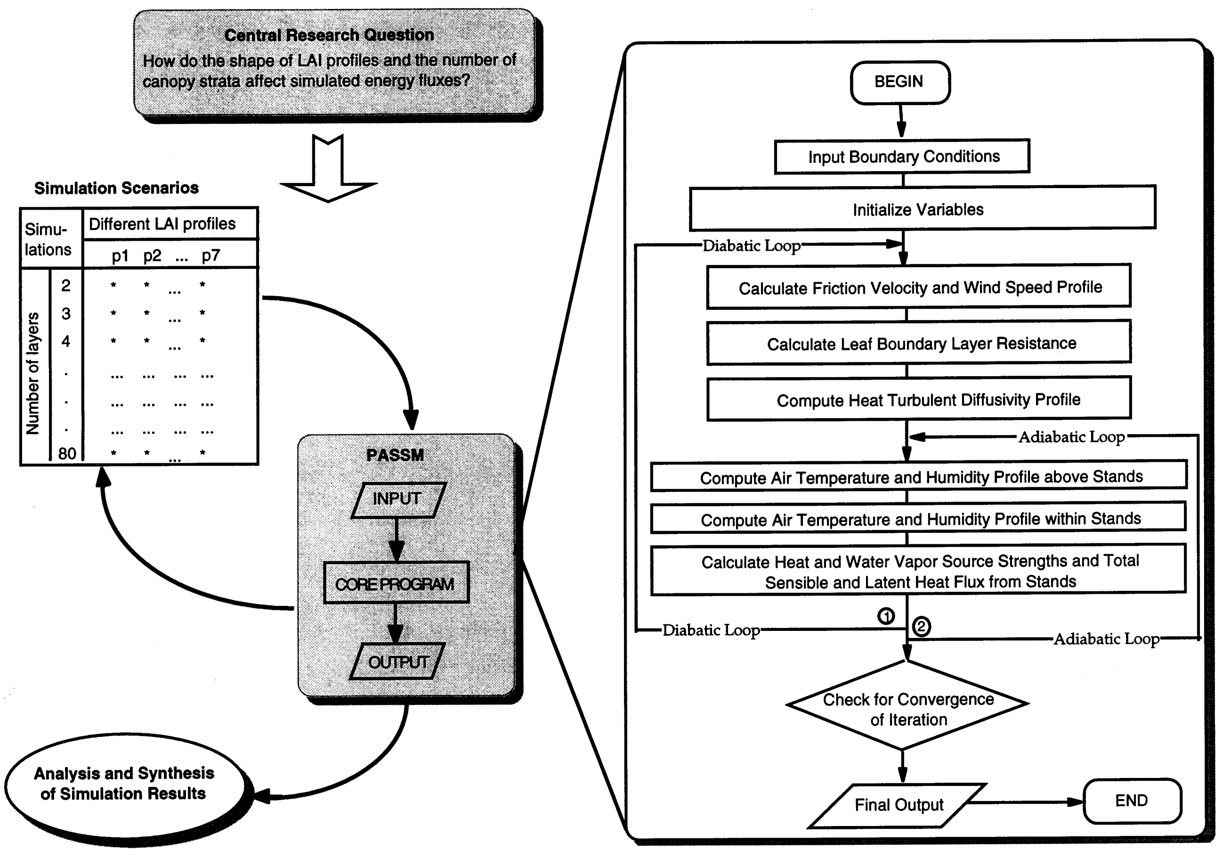

Fig. 3. Conceptual diagram of the simulation study: The effects of the profile of leaf area index (LAI) and number of canopy strata used in a multiple-layered model on simulated energy fluxes are investigated through a series of simulations following a factorial design.

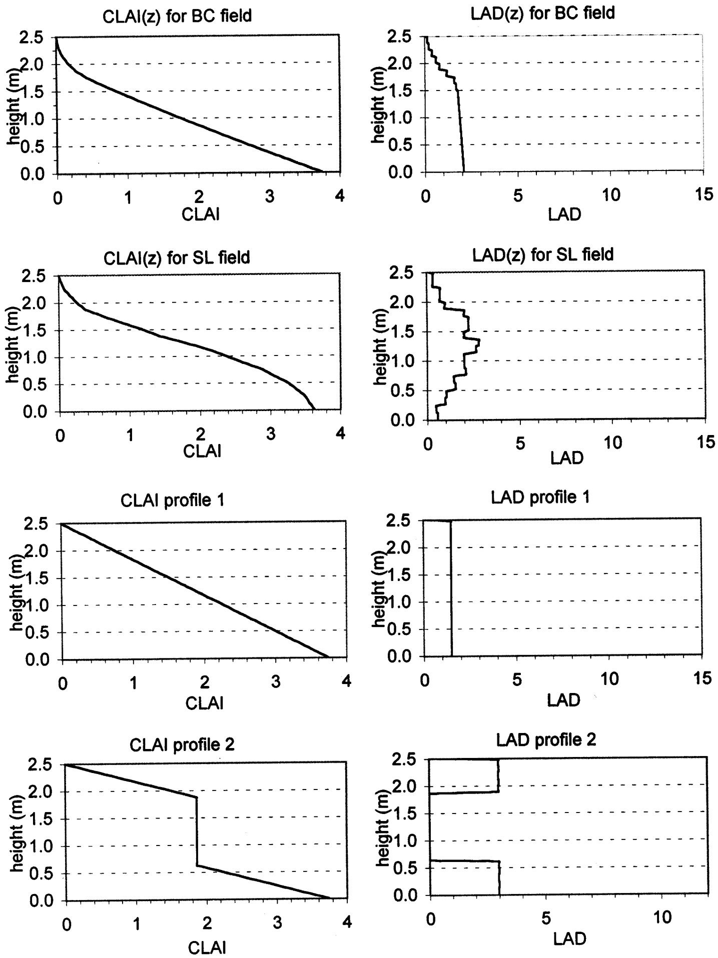

Fig. 4. Different profiles of cumulative leaf area index (CLAI) and leaf area density (LAD) used for the simulation study. The CLAI curves were drawn based on 81 points (i.e. 80 layers), and LAD(z) were computed accordingly. $CLAI_{z=0}$ was 3.74 for BC field, 3.63 for SL field, and 3.74 for all the other profiles.

In our study, we had CLAI(z) as input data and calculated the corresponding LAD(z) using the following difference equation:

$$\mathrm{LAD}(z_i) = \frac{\mathrm{CLAI}(z_i + \Delta z) - \mathrm{CLAI}(z_i)}{\Delta z} \quad (i = 1, 2, \ldots, n) \tag{12}$$

where Δz is the layer depth.

All the leaf area profiles shown in Fig. 4 are based on 80 layers. The CLAI(z) curves appear continuous, whereas the LAD(z) curves show the discreteness due to the layer stratification. The first two pairs of leaf area profiles are empirical data for the BL field and SL field which were used for the validation of PASSM. We created five other leaf area profiles to reflect the possible variations in plant communities, ranging from simple linear to complex curvilinear shapes (profiles 1–5 in Fig. 4). These profiles seem to resemble, to some extent, those observed for different plant communities by Tappeiner and Cernusca (1998). To assure comparability, values of the total cumulative leaf area index ($CLAI_{z=0}$) for all profiles were kept the same or very similar. The value of $CLAI_{z=0}$ was 3.74 for BC field, 3.63 for SL field, and 3.74 for all the other profiles. To

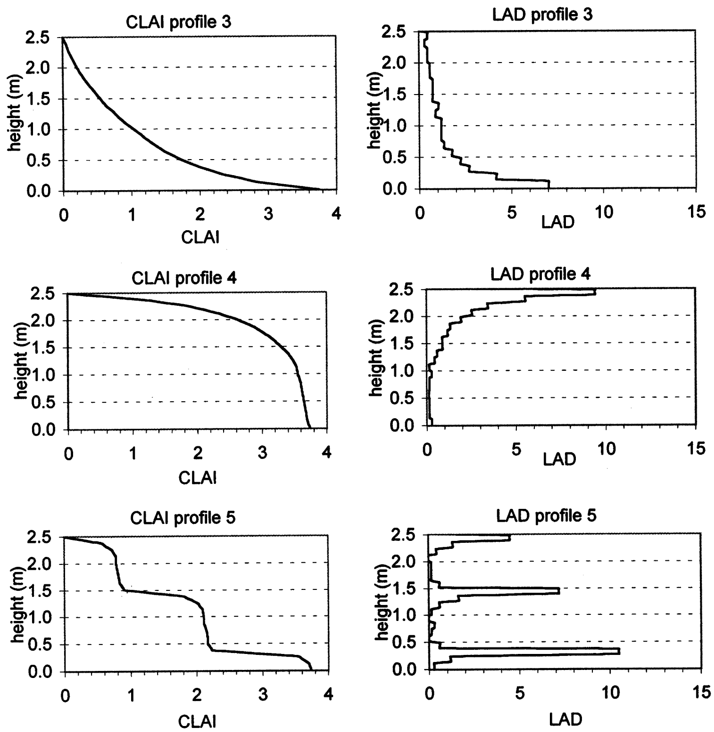

Fig. 4. (*Continued*)

investigate the effects of the number of layers, each leaf area profile was divided into 2, 3, …, 80 strata, respectively, and simulation runs were conducted for each layer number and each leaf area profile. Fig. 5 illustrates how the shape of CLAI profile changes when the number of layers is varied for selected cases. As expected intuitively, larger differences occur with CLAI profiles that are highly nonlinear (e.g., Profile 2, Profile 3, and Profile 5).

4. Simulation results

4.1. Effects of different leaf area profiles on simulated energy fluxes

Our simulation results showed that, with the same set of model parameters and input data, different shapes of the cumulative leaf area index profile (or leaf area density profile) could significantly alter the simulated sensible and latent flux densities even if the total amount of leaves above ground (as indicated by $CLAI_{z=0}$) was the same (Fig. 6). These effects of changing leaf area profiles on simulated energy fluxes were observed no matter how many layers the canopy was divided into. For clarity, Fig. 6 included only 4 out of 80 different simulation scenarios with regard to the number of layers (i.e. 10, 20, 40, and 80). The change pattern between different leaf area profiles with varying layer stratification schemes seemed more consistent for simulated latent heat fluxes than for sensible heat fluxes. As expected, similar leaf area profiles (e.g., BC field, SL field and profile 1) produced more similar values of sensible and latent heat flux densities. On the other hand, leaf area profiles of rather different shapes resulted in larger differences in simulated energy fluxes (e.g., compare Profile 1 with Profile 3 or Profile 3 with Profile 5 in Fig. 6).

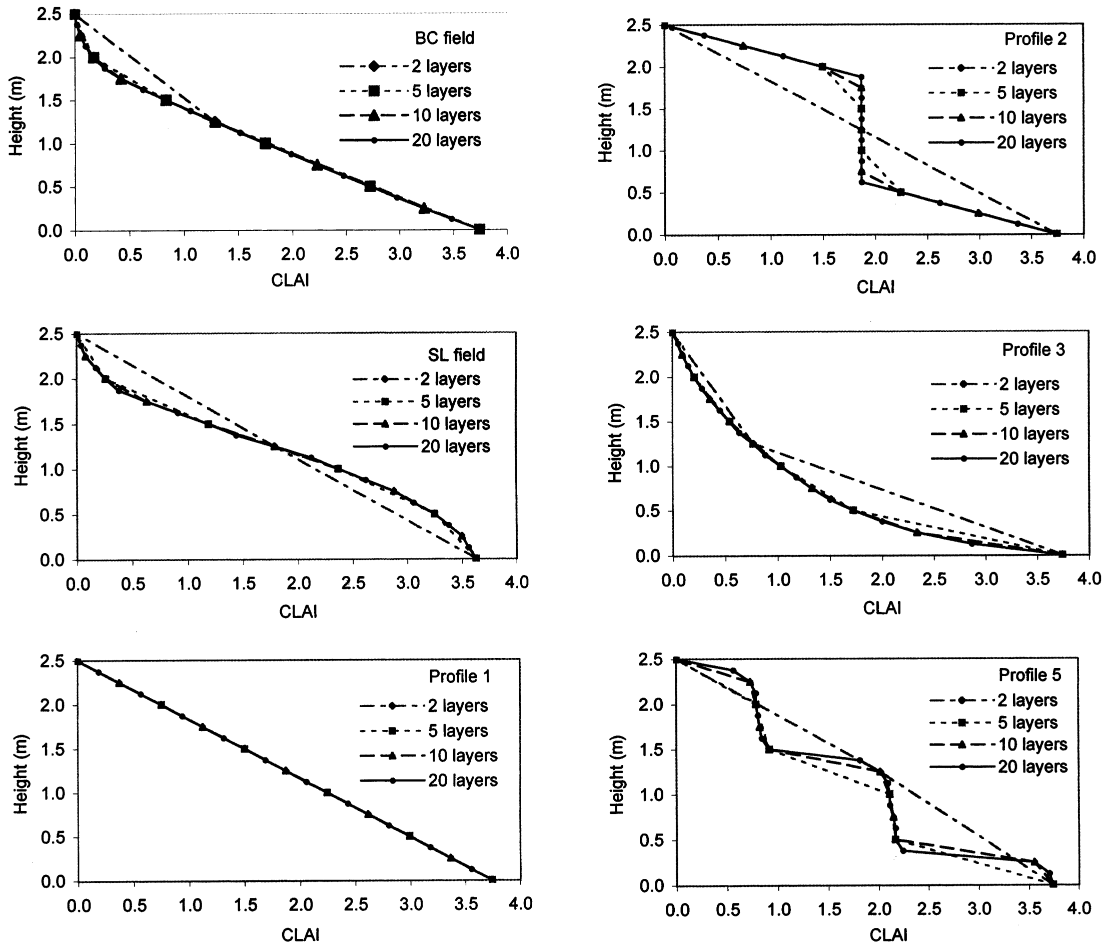

Fig. 5. Illustration of the differences in the shape of the CLAI curve caused by dividing the canopy into different numbers of layers (2, 5, 10, and 20, respectively).

4.2. *Effects of changing the number of canopy layers on simulated energy fluxes*

Changing the number of canopy layers in the model also had considerable effects on the simulated sensible and latent heat flux densities (Figs. 7–9). A general pattern of the canopy stratification effect was that simulated energy fluxes increased with the number of layers following a S-shaped trajectory (Figs. 7–9). The accuracy of simulated energy fluxes increased continuously with the increasing number of layers in the same fashion, although this seemed less evident for sensible heat than for latent heat when the number of layers was large (see Fig. 8). Apparently, there existed a minimal or optimal number of layers for such a multiple-layered biophysical model below which energy fluxes were seriously underestimated and above which incremental improvement in model prediction by further increasing the number of layers became smaller and smaller.

From Figs. 6 and 9 it is evident that the shape of the leaf area profile and the number of canopy layers affected the simulated energy fluxes separately and interactively. For example, the staircase-like CLAI profiles (Profile 2 and Profile 5) produced the largest differences in simulated sensible heat flux while the exponential decay type

(Profile 3) rendered the least variation in both sensible and latent heat fluxes as the number of layers was varied from 10 to 80 (Fig. 6). Not surprisingly, more complex shapes of the CLAI profile seemed to dictate a finer canopy stratification scheme (more layers) than simpler ones in order to achieve the same degree of accuracy in predicting energy fluxes. In particular, Profile 4 and Profile 5 required considerably larger numbers of layers to achieve a high degree of accuracy in simulating energy fluxes (Fig. 9).

The optimum number of layers can be quantitatively determined from the data shown in Fig. 9 using the following first-order difference equation:

$$\frac{\Delta F}{\Delta N} = \frac{F(N_{i+1}) - F(N_i)}{N_{i+1} - N_i} \tag{13}$$

where $\Delta F/\Delta N$ is the rate of change, N_i and N_{i+1} denote the number of layers ($N_{i+1} > N_i$), $F(N_i)$ and $F(N_{i+1})$ are the simulated energy fluxes corresponding to N_i and N_{i+1}, respectively. A relative measure based on (Eq. (13)) may be preferred for it facilitates the determination of the optimum number and its interpretation:

$$\delta = \left(\frac{\Delta F}{\Delta N}/N_{i+1}\right) \times 100 \tag{14}$$

where δ is the percent rate of change, which is a measure of the model improvement for predicting energy fluxes in this case. Starting from the smallest number of layers, eq. (14) can be used repeatedly until δ is equal or close to zero, at which time N_{i+1} becomes the optimum number of layers. When the value of $F(N)$ fluctuates, instead of increasing monotonically (see Fig. 9), the values of δ for the next several consecutive points should also be considered to make sure that the optimum is a global rather than local one. Also, the precision in estimating the optimum number of layers will decrease as ΔN increases from 1, meaning that the number of layers is not progressively incremented by 1 during the simulation. Using this method we determined that the optimum numbers of layers were 34 (SH) and 20 (LE) for simulations in Fig. 8, 20 (SH) and 24 (LE) for profile 1, 24 (SH) and 18 (LE) for profile 3, and 34 (SH) and 64 (LE) for profile 5, when $\delta \geq 1\%$ was used as the cut-off criterion.

5. Discussion and conclusions

Numerous biophysical or biometeorological models treat vegetation as a multiple-layer entity

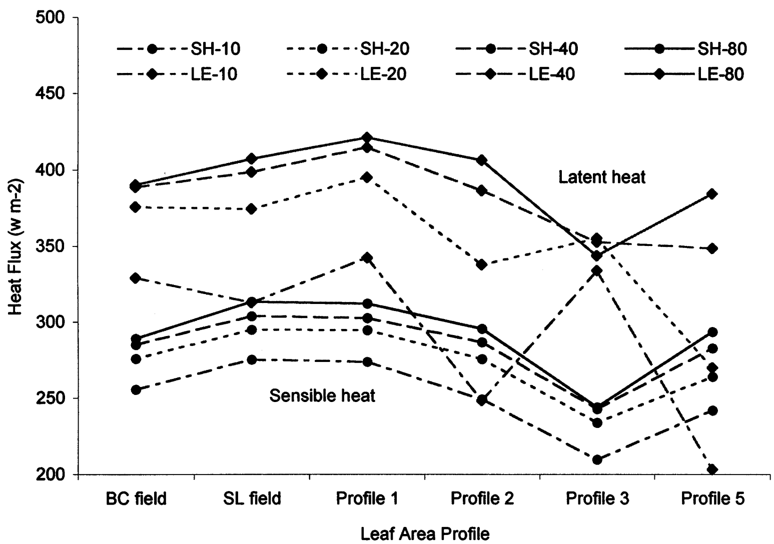

Fig. 6. Simulated sensible and latent heat fluxes for different leaf area profiles and for different numbers of layers (10, 20, 40, and 80). Variations in the leaf area profile and the number of canopy layers both had considerable effects on simulated heat fluxes.

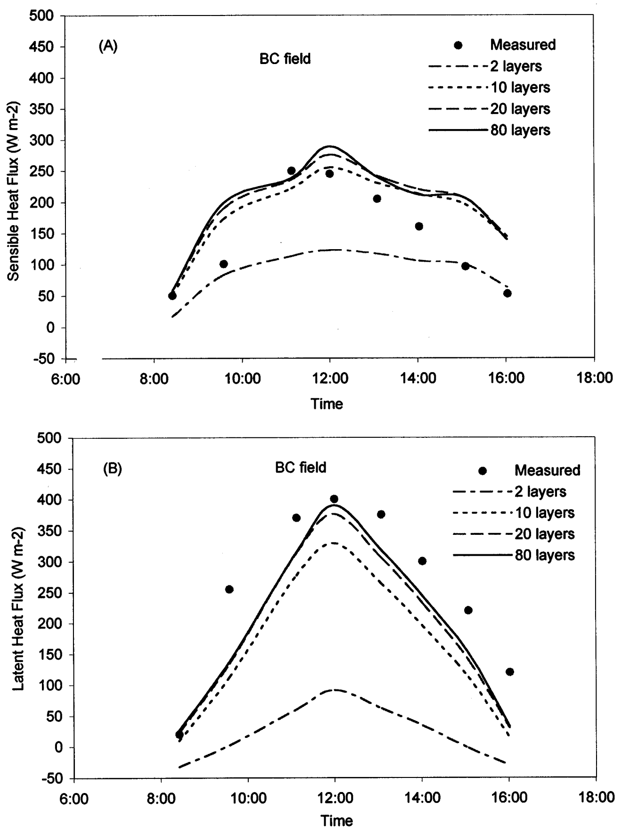

Fig. 7. The relationship between the number of canopy layers in the model and simulated sensible and latent heat fluxes for BC field (input data for 8:25 AM, Sept. 12, 1962).

in order to incorporate detailed mechanistic processes within plant communities (Waggoner and Reifsnyder, 1968; Waggoner, 1975; Goudriaan, 1977; Brutsaert, 1982; Halldin and Lindroth, 1986; Paw U, 1989; Wu, 1990). Usually, the choice of the number of layers in these models is either arbitrary or based on data availability. Thus, it is important to ask: Does changing the number of layers affect model output? If so, how? Is there a general pattern regarding these effects, or are these effects predictable? On the other hand, many process-based ecological models use leaf area index or related measures as a lumped input representing the entire plant community without considering the vertical structure of leaf area distribution (e.g. Running and Coughlan, 1988; Nemani and Running, 1989; Aber and Federer, 1992). Does the vertical structure of leaf area index matter if the total cumulative leaf area index remains the same? How does the shape of the leaf area profile interact with the number of layers to affect the outcome of biophysical models?

We used a process-based, multiple-layered micrometeorological model (PASSM) to address the above questions through a series of simulation experiments. Our results demonstrated that the scheme of canopy stratification could substantially affect the simulated energy fluxes (Figs. 6–9). Importantly, the effect of the number of layers on simulated sensible and latent heat fluxes showed a general pattern which is similar to the logistic growth curve (Figs. 7 and 9). This suggests the existence of a minimal number of layers a model like PASSM must contain in order to achieve a desired degree of accuracy. The value of the minimal number of layers is a function of the allowable error, of course. However, the value that represents the turning point of the S-shaped curve may properly be called the optimal number of layers because the accuracy in model output improves rapidly below it and only slowly above it. The optimal number of layers should indicate a desirable balance between the accuracy of a model and demands for computation and data collection. Thus, the effect of changing number of layers on model outcome is, in principle, predictable.

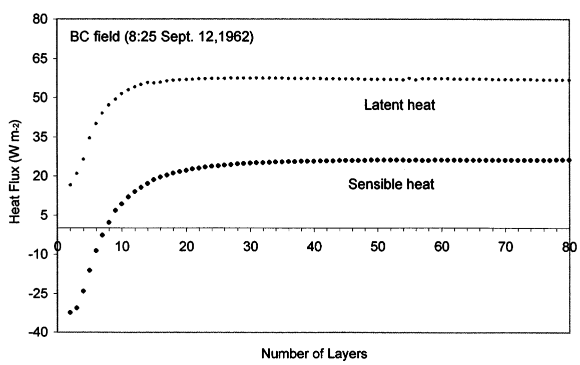

Fig. 8. Effects of changing the number of canopy layers in the model (2, 10, 20, 80) on simulated sensible and latent heat fluxes for BC field (input data for Sept. 12, 1962; measurements from Brown and Covey, 1966).

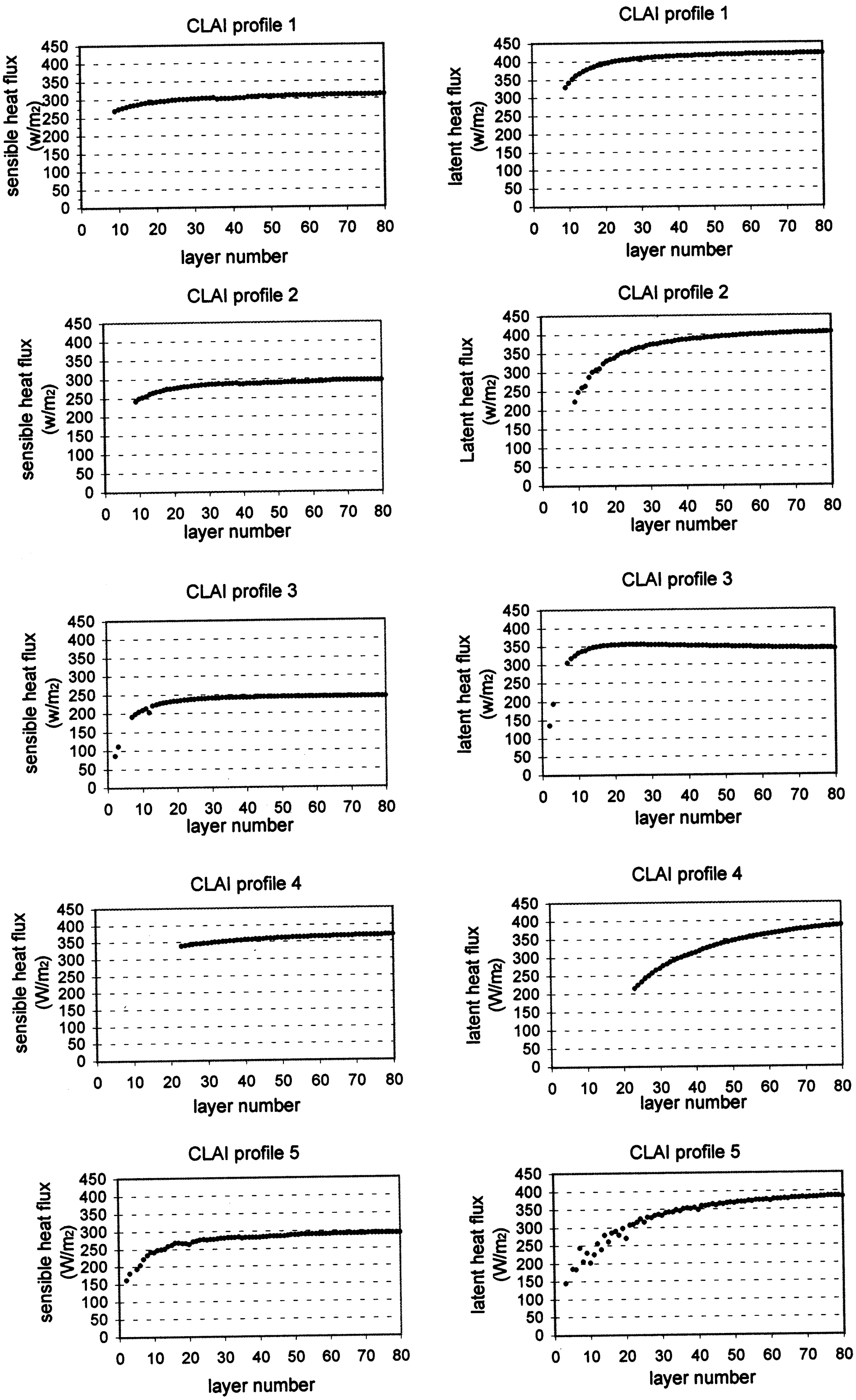

Fig. 9. Simulated sensible (first column) and latent (second column) heat fluxes for five different leaf area profiles as the number of canopy layers was varied from 2, 3, …, to 80. All scenarios exhibited a threshold phenomenon that the simulated heat fluxes continuously increased with the number of layers rapidly up to a certain point and then tended to level off. However, the threshold values differed among leaf area profiles. Missing points in some of the plots were due to the fact that simulations for those numbers of layers did not reach convergence numerically.

Our results also showed that differences in the shape of leaf area profiles alone could significantly alter the simulated energy fluxes even if the total amount of leaves in the canopy and the values of all other model parameters remained the same. This suggests that the details of the vertical structure of canopy are important for assuring a high degree of realism and accuracy for multi-layered biophysical models. Furthermore, the shape of leaf area profiles interacted with the number of layers in affecting the simulated energy fluxes. While considerable impacts were observed for all leaf area profiles, more complex (nonlinear) shapes exacerbated the effects of changing the number of layers (Fig. 6).

The effects of the leaf area profiles and the number of layers demonstrated in this study illustrate the problem of patchiness and scale in the vertical dimension. Spatial patchiness is scale dependent and observed spatial pattern changes with the scale of observation or measurement (Baldocchi, 1993; Wu and Loucks, 1995; Aber et al., 1999; Raupach et al., 1999). This study has demonstrated that the accuracy of the multi-layered biophysical models is affected significantly by the details of the canopy structure, and thus the spatial scale of input data should match that of processes represented by the model. Specifically, the depth of each canopy layer (thus the number of total layers) should be selected in such a way that the processes represented by the equations of a multi-layered model are adequately captured, not over-aggregated.

Having realized that the optimum number varies with LAI profiles and the types of energy fluxes simulated, we suggest, as a rule of thumb, that more than 20 layers seem needed for reducing the effects of canopy stratification to an acceptable level. Having a large number of layers will increase computational demand as well, which should not be a problem for one dimensional models like PASSM. However, both input data requirements and computational demands may become cumbersome in spatially explicit 2-D or 3-D models. A possible solution is to divide the canopy into layers of unequal thickness, with more layers corresponding to regions where LAI changes rapidly. While this will make model coding a little more complex, the total number of layers can be reduced without losing much of model accuracy.

The vertical scale problem needs to be considered in scaling up biophysical and other process-based models. During upscaling, details need to be selectively and systematically filtered out when information is translated over a wide range of scales (Jarvis, 1995; Wu, 1999). It is generally the case that extending detailed models to large spatial scales is limited by overwhelming demands for input and computational power as well as by error propagation and model instabilities. Thus, scaling-up is more likely to be successful by developing different models at different domains of scale and 'chain' them along the 'scaling ladder' than by simply expanding detailed models to cover a large spatial extent (Wu, 1999).

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