11.10 A 3-D MODEL OF MASS AND ENERGY TRANSFERS IN VEGETATED CANOPY

Alice Belot[1*], Jean-Philippe Gastellu-Etchegorry[1], A. Perrier[2]
1. Centres d'Etudes Spatiales de la Biosphère (CESBIO), Toulouse, France
2. Environnement et Grandes Cultures INRA – INA PG, Thiverval Grignon, France

1. INTRODUCTION

Exchanges of energy, water, CO_2 and aerosols between vegetated landscapes and atmosphere play a central role in the dynamics of weather, climate, surface hydrology and terrestrial ecology. These exchanges are regulated and affected by biophysical processes that interact non-linearly with environmental forcing. An approach to quantify these exchanges is through the application of models of mass and energy transfer. These models can be grouped into two main categories: big-leaf models and multi-layer models. A multilayer model integrates the fluxes for each layer to give the total flux, while the big-leaf approach maps properties of the whole canopy on a single leaf before calculating the fluxes. Although complete multilayer models are inevitably complex, they can be powerful tools not only for the prediction of mass and energy exchanges between biosphere and atmosphere but also for the understanding of eco-physiological and physical processes that control these exchanges. A major difference between these methods is how the non-linear relationships describing assimilation and transpiration are parameterized. In this non linearity, canopy architecture plays a major role. Plant geometry not only defines the leaf area distribution but also affects the distribution of solar radiation and turbulent mixing throughout the canopy.

Radiative transfer is the main process that controls energy balance and all biophysical processes while turbulent transport re-distributes the mass and energy fluxes throughout the atmospheric boundary layer (Albertson, 2001). For example, many studies show the necessity to distinguish sunlit and shaded leaves for estimating canopy photosynthesis (Spitters, 1986; Wang, 1998; Myneni and Ganapol, 1992). Most existing models (both big-leaf and multilayer models) suppose that terrestrial surfaces are homogeneous media made of randomly distributed elements that emit and exchange energy and mass fluxes. Account of canopy architecture is expected to improve the simulation of these fluxes.

The importance of canopy architecture led us to develop a 3 dimensional model of mass and energy fluxes. The main objective is to analyse and understand the impact of surface heterogeneities on the exchanges between the biosphere (soil + vegetation) and the atmosphere. This model relies on a realistic description of the studied landscape. A major feature is to fully model the interactions between vegetation and its microclimate, thereby producing realistic solutions that satisfy both the physiological properties and their corresponding microclimate. The model is based on the DART (Discrete Anisotropic Radiative Transfer) model (Gastellu-Etchegorry, 1996). It simulates the 3-D distribution of absorbed radiation by the Earth surface from the visible to the thermal infrared optical domain and also the corresponding canopy directional reflectance and brightness temperature images. It discretizes the studied landscape into cells. Models of leaf and soil functioning and also turbulence are developed according to this representation. Here, we describe the 3D energy model and its algorithm and we present the validation results on two sites in France.

* *Corresponding author address:* Alice Belot, Cesbio, 18 av. Ed. Belin, BPI 2801F, 31401 Toulouse Cedex 9; e-mail: belot@cesbio.cnes.fr

2. MODEL DESCRIPTION

The physical model is a complete canopy energy balance and photosynthesis process scheme. It can be divided into four parts: radiative transfer, turbulence, leaf and soil functioning.

2.1 Landscape representation

Figure 1 shows two types of vegetated landscapes: homogeneous landscape (e.g. developed crops) and a forest. Landscapes are modelled as rectangular matrices of parallelepiped cells (figure2).

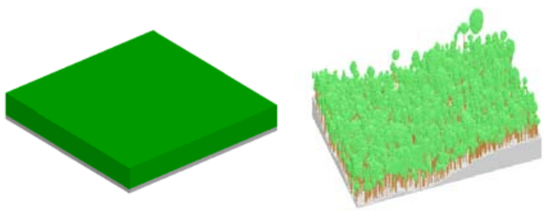

Figure 1: Computer simulation of vegetated landscapes. Homogeneous scene (left). Tropical forest with relief (right)

A large number of natural and urban landscapes can be simulated (e.g. trees with leaves and trunks, grass, lakes, soil and urban components) with specific optical (reflectance, transmittance) and structural (leaf area index LAI, leaf angular distribution LAD) parameters. Leaf and grass cells contain turbid medium. Soil, trunk, lake and urban elements are simulated with opaque triangles or parallelograms. Soil is made of z layers with y soil surface cells par layer. Each soil layer is characterized by a specific texture. (Figure 3). Radiative balance, leaf and soil functioning are computed per cell. Therefore, we can simulate the 3D

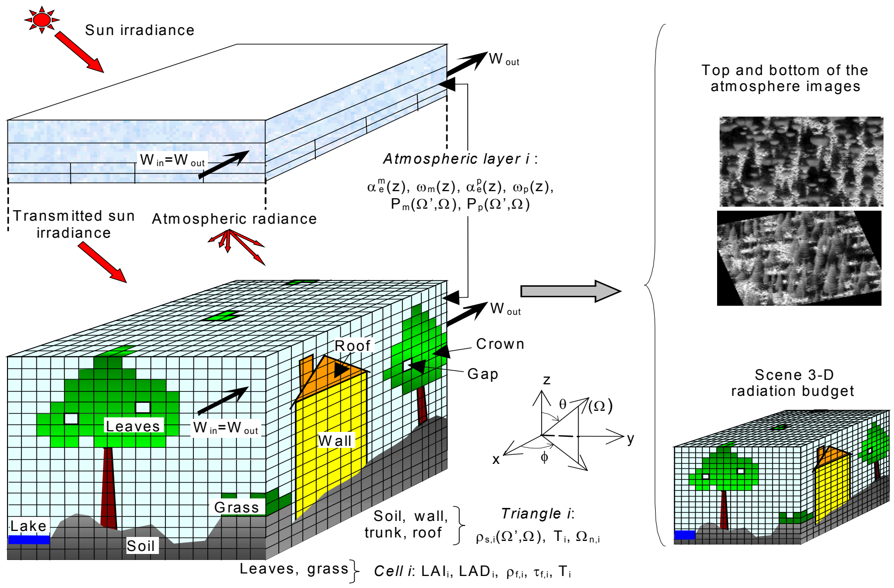

Figure 2: DART representation of the "Earth+Atmosphere" scene and products.

distribution of fluxes (latent, sensible and conduction heat fluxes, net radiation and carbon fluxes) and also the 3D distribution of leaf and soil temperature.

2.2 Radiative transfer and absorption

Radiative transfer is simulated to assess flux densities of visible (VIS), near-infrared (NIR), mid-infrared (SWIR) and thermal infrared (TIR) radiation. DART model (Gastellu-Etchegorry, 1996) simulates radiative transfer in heterogeneous 3-D landscapes over the whole optical domain from 0.3 to 15 μm. Turbid medium within vegetation and air cells gives rise to volume interaction with single and multiple scattering whereas opaque parallelograms and triangles give rise to surface interactions. Radiation propagation is modelled by ray tracing and discrete ordinate methods. DART simulates reflectance and brightness temperature images for any experimental conditions (view direction, type of atmosphere, etc.). It gives also for each cell the radiation regime distribution, i.e. absorbed, intercepted, incident and scattered radiation fluxes. These fluxes are used to calculate leaf photosynthesis, stomatal conductance and also leaf and soil energy balance. DART was already successfully tested against reflectance and brightness temperature measurements in the field.

In our model, incident sun radiation is partitioned into VIS, NIR and SWIR components. Therefore, net radiation R_n is computed for each cell according to :

$$R_{n,cell} = R_{abs,VIS} + R_{abs,NIR} + R_{abs,SWIR} - E_{TIR} \quad (1)$$

where $R_{abs,VIS}$, $R_{Abs,NIR}$, $R_{abs,SWIR}$, are the absorbed radiation in the visible, near infrared and short wave infrared domain respectively and E_{TIR} is the radiative balance in the thermal infrared domain.

DART can simulate radiative transfer in the atmosphere. When data about atmospheric diffuse radiation are not available, atmospheric diffuse radiation is assumed to be isotropic. Its intensity is computed with Spitters equations (Spitters, 1986).

2.3 Turbulence and diffusion

An accurate formulation of turbulence is needed to account for the influence of atmosphere on within canopy transfer processes. The interdependence between absorbed/emitted fluxes and air concentrations of water vapour pressure, CO_2 pressure and temperature requires the use of a turbulent diffusion model. According to Baldocchi (1992), the neglect of vertical changes in water vapour partial pressure and CO_2 concentration does not produce large errors on the prediction of latent heat and CO_2 flux densities. However, an accurate account of air temperature profile is important for simulation of sensible heat flux density. Our turbulence module simulates wind and air scalar profiles within the canopy. Wind speed is modelled with a classical logarithmic law above the canopy and an exponential profile within it (Yamazaki, 1992). Air scalar profiles inside and above canopy are computed with the inverse Lagrangian localized near field (LNF) theory developed by Raupach (1989). It predicts source/sink strengths from concentration profiles and knowledge of the within canopy turbulence field. An iterative scheme must be used because fluxes concentration profiles are unknown variables.

The entire turbulence module works with an horizontally homogeneous canopy. It means that scalar concentrations which are calculated for each cell of the scene with the leaf module (described in the next paragraph), are averaged values per layer.

2.4 Leaf biochemical model

The mechanistic model of Collatz (1991) is used to compute photosynthesis, CO_2 assimilation and stomatal conductance. This model has the advantage to require few parameters. It describes the leaf net carbon assimilation A_n as the minimum of three limiting factors minus the leaf dark respiration, R_d. These limiting factors are: W_c relative to the carboxylation amount and to the leaf enzymatic capacity, W_e relative to the absorbed photosynthetic active radiation (APAR) and W_s relative to the carbon compound export. Thus, we have for any cell :

$$A_{n},_{leaf,cell} = min(W_c, W_e, W_s) - R_{d,cell} \quad (2)$$

A_n calculation is combined with the Ball and Berry semi-empirical model for simulating leaf stomatal conductance, $g_{s,cell}$. Stomatal conductance responds directly to the within leaf assimilation rate with a general optimisation strategy that seeks to maximize carbon gain while minimizing water loss. It depends explicitly on surface humidity and on CO_2 pressure. It depends also implicitly on leaf surface temperature, absorbed PAR and internal CO_2 pressures via the dependence on A_n. To simulate the effect of leaf water deficit on stomatal conductance and net photosynthesis, a parameter that characterizes soil stress is introduced according to Leuning (1995).

Leaf boundary layer conductance, $g_{b,cell}$, controls transfer of carbon, heat and water vapour from leaf surface to canopy air space. It is obtained from relations given by Nikolov (1995).

Once carbon assimilation and conductances are known, fluxes of carbon, water and heat from leaf to or from the atmosphere are described by the Ohm's analogy.

2.5 Soil Model

The CO_2 efflux from the soil comes from plant root and micro-organisms respiration. Epron (1998) proposed an empirical relationship between soil CO_2 efflux and both soil temperature, $T_{soil,cell}$, and soil water content at a depth of 10 cm, θ_{10cm}:

$$R_{soil,cell} = A.\theta_{10cm}.exp(B.T_{soil,cell}) \quad (2)$$

where A and B are two parameters that must be fitted with measurements. By default, they are fixed to 1.13 and 0.136 respectively.

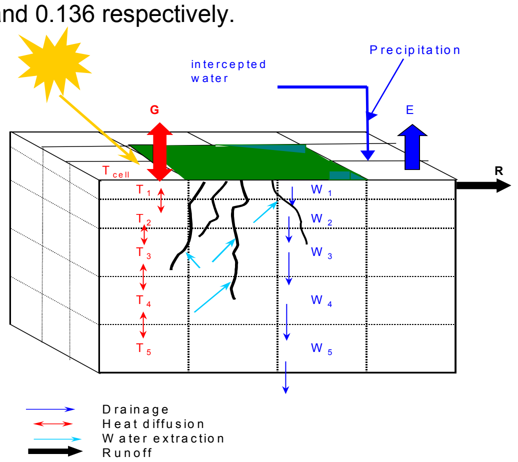

Figure 3: Soil discretisation. Roots are located uniformly within each soil layer.

Diffusion of heat and water in the soil is computed according to the ISBA-DF soil module (Noilhan, 1996; Boone, 1999, 2000). It takes into account the vertical distribution of temperature (T_i), liquid water (w_i), soil texture and root zone. Neglecting the ice content, the heat and mass transfer equations for any soil layer i are:

$$c_g \frac{\partial T_i}{\partial t} = \frac{\partial G_i}{\partial z} \text{ and } G_i = \lambda.\frac{\partial T_i}{\partial z} \quad (3)$$

$$\frac{\partial w_i}{\partial t} = -\frac{\partial F_i}{\partial z} - \frac{S_L}{\rho_w} \text{ with } w_{fc} < w < w_{sat} \quad (4)$$

with λ the thermal conductivity, c_g the heat conduction coefficient, G_i the heat conduction flux, F_i the soil water flux, and S_L a liquid water source/sink due to evapotranspiration or lateral flux. The soil water flux is computed following the Darcy's law. More details can be found in Boone (1999,2000).

Knowledge of the distribution of soil surface temperature and humidity at the previous time step allow one to compute for each soil cell, heat and water profiles and heat conduction flux. Sensible heat flux and evaporation are then computed according to gradient diffusion law. These exchanges between soil and the first air layer are limited by soil aerodynamic resistance, r_{as}. This resistance is computed according to the work of Daamen and Simmonds (1996) with a thermal stability near soil surface. Moreover, an additional soil resistance is needed to prevent excessive soil evaporation. It limits water vapor exchanges from the soil pores to the immediately overlying air. The expression of Camilo (1986) is used.

3. MODEL PARAMETERIZATION

As a first approximation, the model relies on the hypothesis that energy balance must be verified everywhere in the scene, i.e. in each cell. In order to meet this energy balance, our model uses an iterative approach: an inner loop used to assess the within canopy air scalar profiles is included within a loop on leaf temperature. Major steps of the model are given below (Figure 5):

- DART simulates canopy radiation regime in the short wavelengths spectral domain.
- The wind speed profile and dispersion matrix are computed. (Figure 5, Turbulence1)
- DART simulates the 3D radiation regime in the thermal infrared spectral domain. At the first time step, it uses an initial guess of leaf and soil temperatures. Otherwise, it uses the temperature distribution of the previous time step. At this stage, the net radiation R_n is known.
- Air scalar profiles are set to their value at the reference point above the canopy. For each cell, the leaf module simulates for each leaf cell carbon assimilation $A_{leaf,cell}$ and conductances. Then latent flux $LE_{leaf,cell}$ is computed. Sensible heat flux $H_{leaf,cell}$ is such that the energy balance is verified for each cell:

$$H_{leaf,cell} = Rn_{leaf,cell} - LE_{leaf,cell} - An_{leaf,cell} \quad (6)$$

- Soil fluxes are computed. Profiles of heat and water in each soil column are estimated. Heat conduction flux, $G_{soil,cell}$, and evaporation, $LE_{soil,cell}$, are computed. The energy balance gives the sensible heat flux for each soil surface cell:

$$H_{soil,cell} = Rn_{soil,cell} - LE_{soil,cell} - G_{soil,cell} \quad (7)$$

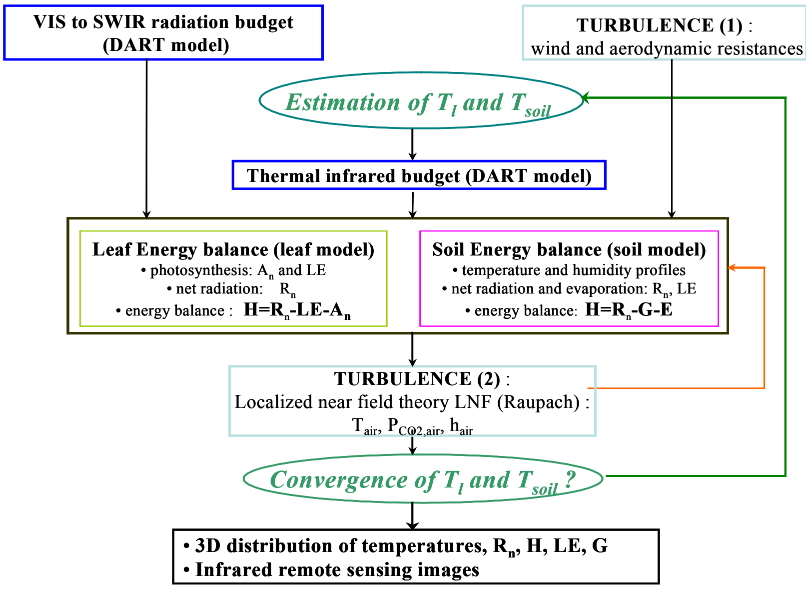

Figure 4: Algorithm of the 3D energy model.

- Once all source/sink strengths are known for each cell, the micrometeorological module runs to provide air scalar profiles. 3 to 5 iterations are necessary until all air scalar profiles converge. (Figure 5, Turbulence2)
- The heat flux $H_{leaf,cell}$ estimated by the energy balance is compared with the one estimated by the Ohm's analogy relation for each soil and leaf cell:

for leaf: $$H_{leaf,cell} = 2.\rho_a.c_p.\left(T_{f,cell} - T_{a,i}\right)/r_{b,f,cell}, \quad (8)$$

for soil: $$H_{soil,cell} = \rho_a.c_p.\left(T_{soil,cell} - T_{a,1}\right)/r_{b,f,cell}, \quad (9)$$

where ρ is the air density, c_p the specific heat, $T_{leaf,cell}$ the leaf cell temperature and $T_{a,i}$ the corresponding air layer temperature. If there is no equality, a new leaf temperature is assessed in order that H verifies the energy balance for each cell. Generally, convergence on temperatures is reached with 3 iterations.

4 MODEL TESTING

4.1 Sites characteristics and measurements

The MUREX experiment site is a fallow land, located 30 km from Toulouse, Southwest France (43°24'N; 1°10'E). It had remained fallow during two years before the beginning of the experiment. A weather station operated by the CNRM (Centre National de la Recherche Météorologique) during three years provides climatic variables averaged with a 30-min time step: air temperature and humidity at 2m height, wind speed and direction at 10m height, incoming solar and long wave radiation, reflected solar radiation and precipitation continuously (Calvet, 1999). Vegetation comprises of about forty herbaceous plant species, forming a dense closed canopy. Dominating species (*Brachypodium, ramosum/Pinnatum,* and *Potentilla reptans*) represent 75% of the total species. Leaf area index and vegetation height were monitored regularly throughout the three years.

The second site, Le Bray, is part of the EUROFLUX programme (Aubinet et al, 1999). It is located near Bordeaux in France (44°43' N, 0°46' W). It is composed of maritime pine plantation (*Pinus pinaster* Ait*)*. Trees are 34 years old. They are distributed in parallel rows along a NW-SW axis. The inter-row distribution is 4 m (Lamaud et al., 2001). Canopy height is 18 m with a 2.8 mean leaf area index. The site has a fetch larger than 600 m for the prevailing wind direction (N and W) and the ground surface is flat. The canopy can be divided into 3 parts: the upper one, between 12 and 18 m made by pine crowns, the middle one (1-12 m) corresponding to the trunks and the lowest one (0-1 m) consists mainly of grass (*Molinia coerulea* Moench). The soil is a hydromorphic podzol with sand agglomerate at a depth of about 0.5 m. It is covered by a litter with an average thickness of 0.05m. Measurements have been made from autumn 1996 till 1999. The dataset used here covers year 1997. Net radiation, incident and upward solar radiation, air temperature, air specific humidity and air pressure were measured at 25 m aboveground every 10s and averaged every 30min. Wind speed, friction velocity and sensible heat flux were measured at the same level with a 3D sonic anemometer. Water vapour and carbon dioxide fluxes were measured with the sonic anemometer coupled with an infrared gas analyzer. Incoming long-wave radiation was deduced from net and solar radiation measurements. All physiological parameters are taken from Ogée et al. (2003).

4.2 Results

4.2.1 Murex site:

A simulation over 15 days from 26/05/1955 (day 146) to 10/06/1995 (day 151) was carried out. These days are characterized by a strong variation of the cloud cover and by a fallow cut on day 150. During that period, canopy leaf area varies from 3.11 to 0.33

after the fallow cut. No atmospheric data were available; therefore Spitters equations (Spitters, 1986) were used to model diffuse solar radiation. The purpose of this study is to validate the 3D model on a simple grass cover, to be sure that environmental processes are well modeled. Model results will be confronted with measurements but also with results obtained with the ISBA model (Noilhan, 1996; Boone, 1999), a 1D big leaf model.

	Rn	H	LE	G
r^2	0.997 *(0.997)*	0.866 *(0.77)*	0.94 *(0.89)*	0.92 *(0.73)*
slope	1.02 *(1.001)*	1.05 *(0.69)*	0.92 *0.98)*	0.99 *(1.86)*
intercept	5.8 *(18.22)*	5.1 *(15.98)*	19.9 *(19.73)*	6.7 *(10.53)*
RMSE	18.16 *(9.35)*	39.36 *(20.17)*	40.1 *(42.37)*	10.48 *(32.54)*
Bias	-9.3 *(19.5)*	7.04 *(5.12)*	-12.6 *(18.3)*	-8.8 *(-31.7)*
d	0.997 *(0.996)*	0.908 *(0.85)*	0.97 *(0.97)*	0.928 *(0.75)*

Table 1: Regression analysis of the DART based model and ISBA model (between brackets) against MUREX measurements. (d is the index of agreement of Willmott, 1981).

Our 3D model simulates measurements with good accuracy, which is very encouraging (see figure 5). All statistical results (Table 1) are rather good. Slopes of linear regressions are closed to 1, intercept are closed to 0, r^2 are higher than 0.87 and values for the agreement index of Willmott, d, are close to 1 as required for perfect agreement. Root mean square errors (RMSE) are satisfactory.

Compared to ISBA, our model gives better results, especially for heat ground conduction flux. Moreover, ISBA evapotranspiration is strongly overestimates at midday. During the night, ISBA sensible and latent heat fluxes are very small, whereas our model gives too large values. This is mainly due to thermal stability that occurs at night. This phenomenon is not well modeled by our model. It will be improved through an optimisation study that will lead to a better estimation of input parameters (maximum rate of carboxylation by Rubisco, Ball and Berry coefficients and parameters for soil resistance). This study will probably correct the present underestimation of sensible heat fluxes in the evening and at night. Moreover, a more realistic representation of the scene with the possibility of having a bare soil could also improve results.

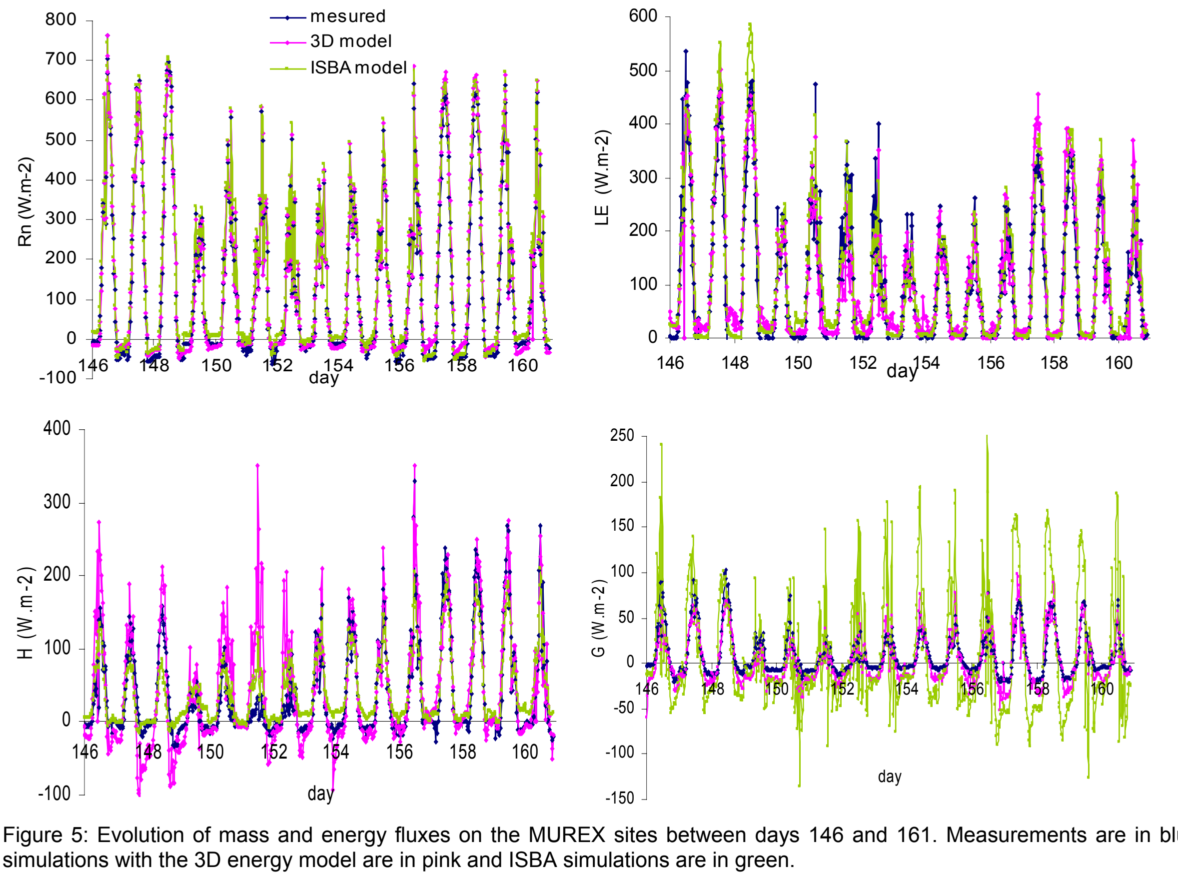

Figure 5: Evolution of mass and energy fluxes on the MUREX sites between days 146 and 161. Measurements are in blue, simulations with the 3D energy model are in pink and ISBA simulations are in green.

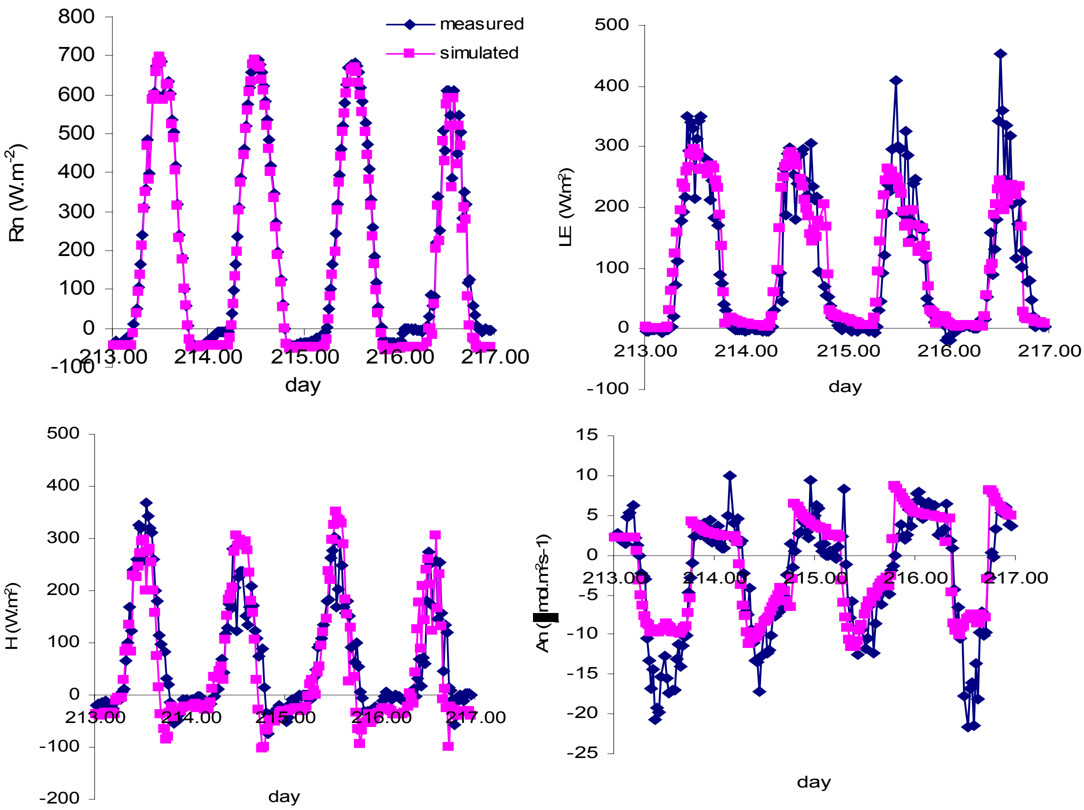

Figure 6: Evolution of mass and energy fluxes on the Bray site between days 213 and 217. Measures are in blue, simulations with the 3D energy model are in pink.

4.2.2 Bray site

Simulations were carried out over 4 sunny days (from 01/08/1997, day 213, to 04/08/1997, day 217). Simulated fluxes are close to measurements, with very similar time variations (Figure 6). All statistics results are satisfactory (Table 2).

	Rn	H	LE	A_n
r^2	0.99	0.88	0.9	0.73
slope	1.06	1.1	0.93	0.7
intercept	-1.3	-0.94	27.1	0.28
RMSE	17.2	56.4	46.5	2.04
Bias	2.24	12.69	-3.2	-6
d	0.99	0.93	0.94	0.9

Table 2: Statistics related to the Bray site.

Except for carbon fluxes, slope of linear regressions are close to 1, intercept are low, r^2 are higher than 0.88 and values of the agreement index of Willmott (1981) are close to 1. Poorer predictions are for net carbon assimilation. It is often strongly underestimated (e.g. during midday 213). This means that photosynthesis saturation by solar radiation is too strong, which is probably due to an inaccurate calculation of leaf nitrogen content. Root mean square errors are relatively large for sensible and latent heat fluxes. However, they correspond to random errors without bias. This shows that our 3D model is able to simulate mass and energy exchanges in a forest with trees along rows.

5. CONCLUSIONS

A complex 3D energy balance model has been developed. It simulates major mass and energy processes that occur in the canopy. Its accurate simulation of radiative transfer make it an useful tool for studying the effect of canopy architecture on the 3D distribution of radiation, energy and mass fluxes and also leaf and soil temperature. It has the great advantage to be adapted to many different landscapes. This complete model has been tested against two field measurements, one on a fallow and the other on a pine forest. Most simulated fluxes are close to measurements. However, some calibrations are needed to improve our model. Simulations with a big leaf model, the ISBA model, allowed us to show more accurate parameterization of leaf and soil processes gives relatively better results. Thus, results are very encouraging. In a further step, other validation will be carried out on an olive tree site in Morocco where climate and tree architecture are very different from those already studied.

After being fully tested and validated, this model is expected to be an efficient tool for a wide range of applications: from the leaf and soil functioning to remote sensing applications. It will be helpful to better understand interactions between vegetation architecture and its functioning which should lead to emergent properties that could be used in simpler models. Thanks to its radiative module, it can simulate thermal infrared images with temperatures that verify the energy balance at each point of the scene. It can be therefore a useful tool for studying vegetation functioning using remote sensing images.

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