Modelling of the Moisture and Heat Flux at the Vegetated Landsurface

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The moisture and heat transfer in the SPAC are studied by establishing a coupled full-interacting physical SPAC model. A vegetation model which preserves the essential mechanisms is employed to describe the vegetation as simply as possible. The required input data in atmosphere are limited to only four, being net radiation, wind speed, vapor pressure, and air temperature, so that the present method can be easily applied in practical problems. Finally, the present model is verified by a field observation.

Keywords: Moisture flux, Heat flux, Evapotranspiration,
Soil-Plant-Atmosphere Continuum (SPAC)

1. INTRODUCTION

The interaction between earth's surface and atmosphere is a very important process which concerns with a variety of scientific problems, including water circulation, climate evolution, seed generating, plant growth, weather prediction and so on. In order to understand well the interaction it is essential to determine the fluxes of momentum, latent heat, and sensible heat at the land-atmosphere interface which is a boundary layer, containing vegetation and adjacent soil and air, saying Soil-Plant-Atmosphere Continuum (SPAC). For their own purposes many researchers have been involved in the study of exchange of energy and mass in the SPAC, but most of them pay more attention on their own field of soil, vegetation or atmosphere respectively by assuming remaining parts are in ideal or simple conditions. In recent years it is found that the coupled full-interacting system of the SPAC should be taken into consideration although the isolated and idealized analyses of the three components of the SPAC are also important and should be developed prior to the development of the theory of their coupled behavior (Milly, 1991).

Among the soil, vegetation, and atmosphere, vegetation is a more important regime than remaining two, since the presence of the vegetation greatly affects, and often largely controls the fluxes of mass, energy, and momentum of the landsurface. On the other hand, this greatly complicates the estimation of these fluxes as the number and complexity of the processes taken place in living organisms increase. Therefore, although many vegetation models have been developed, such as the Simple Biosphere model (SiB) (Sellers et al, 1986) and the Biosphere Atmosphere Transfer Scheme (BATS) (Dickinson et al, 1986), the applications of these models are still limited because of the complexity of the vegetation and a large amount of data requirements.

Obviously, it is not possible to include all biophysical and biochemical processes into the vegetation model, but the important processes must be involved into the model, otherwise the mechanisms of moisture and heat transfer in the SPAC could not be simulated correctly. The purpose of the present study is to establish a physi-

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cally based, coupled, full-interacting SPAC model and its numerical simulation procedure to describe the moisture and heat transfer in soil, vegetation, and atmosphere. For the vegetation model, core of the SPAC, the parameters, which describe the physics and preserve the essential mechanisms that control the energy and water balance at the surface, are kept as low as possible, so that the present method can be easily applied to practical problems. For instance, the required input data in atmosphere are limited to only four, being net radiation, wind speed, vapor pressure, air temperature. They are all regularly observed data which can be obtained at meteorological observation stations. Finally the present model is validated by field observation data which obtained in Yucheng in northern China.

2. MODEL STRUCTURE

2.1 Soil Moisture and Heat
The mechanistic model was developed for heat and mass flows in a partially saturated porous media (Philip and de Vries, 1957). The corresponding equations modified by Witono and Bruckler (1991), the coupled, diffusion-type, partial differential equations, are employed in this study. The conservation equations are

$$\rho_l C_w \frac{\partial h}{\partial t} = -\frac{\partial J_w}{\partial z} - S_w \tag{1}$$

$$C \frac{\partial T}{\partial t} = -\frac{\partial J_T}{\partial z} \tag{2}$$

where h is the pressure water head; T the soil temperature; J_w and J_T the moisture and heat flux; S_w the intensity of the root uptake, C_w and C the specific soil moisture capacity and the volumetric heat capacity; ρ_l the density of liquid water. The moisture flux consists of liquid water flux J_l and water vapor flux J_v, such that:

$$J_l = -\rho_l \left(D_{lh} \frac{\partial h}{\partial z} + D_{lT} \frac{\partial T}{\partial z} + D_{lh} \right) \tag{3}$$

$$J_v = -\rho_l \left(D_{vh} \frac{\partial h}{\partial z} + D_{vT} \frac{\partial T}{\partial z} \right) \tag{4}$$

where D_{lh} and D_{lT} are the liquid hydraulic conductivity and the thermal liquid diffusivity, D_{vh} and D_{vT} the isothermal vapor conductivity and the thermal vapor diffusivity, respectively. Since $J_w = J_l + J_v$, the expressions of J_w and J_T are as follows,

$$J_w = -\rho_l \left(D_{hh} \frac{\partial h}{\partial z} + D_{hT} \frac{\partial T}{\partial z} + D_{lh} \right) \tag{5}$$

$$J_T = -D_{TT} \frac{\partial T}{\partial z} - D_{Th} \frac{\partial h}{\partial z} \tag{6}$$

where D_{hh} and D_{hT} are isothermal moisture conductivity and thermal moisture diffusivity, D_{TT} and D_{Th} the apparent thermal conductivity and the transport coefficient for heat flow, respectively.

2.2 Intercepted Water
The rainfall and dew water intercepted by the vegetation feed a storage of water within vegetation, being called intercepted reservoir. The intercepted water evaporates into the atmosphere at the potential evaporation rate from the fraction δ of the foliage covered with a film of water, meanwhile the water contained in the vegetation transpires from remaining part $(1-\delta)$ of the foliage. The equation of the water storage in the vegetation can be expressed as

$$\frac{\partial W_r}{\partial t} = veg \cdot P - E_r - R_r \tag{7}$$

where, W_r is the water content of the intercepted reservoir, veg the fraction of the vegetation, P the precipitation, E_r the evaporation from vegetation of the fraction of δ. And R_r is the runoff of the intercepted reservoir, which occurs when W_r exceeds the maximum water content of the reservoir, $W_{rmax} = 0.2 \times 10^{-3} \cdot veg \cdot LAI$, in which LAI is the leaf area index.

2.3 Surface Fluxes

Following the basic equations of Noilhan and Planton (1989), the surface fluxes of momentum, moisture, and heat as well as the aerodynamic and surface resistance can be calculated through following equations.

(a). Sensible heat flux, H

$$H = \rho_a C_p \frac{T_s - T_a}{r_a} \tag{8}$$

where ρ_a is the density of the air, C_p the air specific heat, r_a the aerodynamic resistance, T_s and T_a the temperature of ground surface and air, respectively.

(b). Evaporation from soil surface, E_g

$$E_g = (1 - veg)\rho_a \frac{h_u q_{sat}(T_s) - q_a}{r_a} \quad \text{with} \quad h_u = exp\left(\frac{hMg}{RT_s}\right) \tag{9}$$

where $q_{sat}(T_s)$ is the saturated specific humidity at the temperature T_s, q_a the atmosphere specific humidity at reference height, h_u the relative humidity at the ground surface, R the gas constant of vapor, M the molecular weight of water vapor, g the gravitional acceleration.

(c). Evaporation from the fraction δ of the foliage covered by a water film, E_r

$$E_r = veg \rho_a \delta \frac{q_{sat}(T_s) - q_a}{r_a} \quad \text{with} \quad \delta = \left(\frac{W_r}{W_{rmax}}\right)^{\frac{2}{3}} \tag{10}$$

(d). Transpiration from remaining part $(1-\delta)$ of the foliage, E_{tr}

$$E_{tr} = veg \rho_a (1-\delta)\frac{q_{sat}(T_s) - q_a}{r_a + r_s} \tag{11}$$

where r_s is the surface resistance. In the case of $q_{sat}(T_s) \leq q_a$, $\delta = 1$ in Eq.(10) and Eq.(11).

(e). Aerodynamic resistance, r_a

The calculation of r_a is based on Monin-Obukhov similarity theory and the Monin-Obukhov length L is employed to express the stability of atmosphere, such that:

$$r_a = \frac{1}{\kappa u_*}\left\{ ln\left(\frac{z - z_d}{z_{oh}}\right) - \Psi_h(\xi)\right\}$$

with $\quad u_* = \dfrac{\kappa u}{\left\{ ln\left(\frac{z - z_d}{z_{om}}\right) - \Psi_m(\xi)\right\}}$, $\xi = \dfrac{z - z_d}{L}$, and $L = \dfrac{-u_*^3 \rho_a}{\kappa g\,(H / T_a C_p + 0.61E)}$ (12)

where κ is the von Karmon constant (=0.4), u_* the friction velocity, z the height of atmospheric measurement above ground, z_d the displacement height, z_{om} and z_{oh} the roughness height for momentum and heat ($z_{oh} = 0.2 z_{om}$), E the total evapotranspiration ($E = E_g + E_r + E_{tr}$). The value of z_d and z_{om} are estimated from the height of the vegetation h_t , $z_d = 0.63 h_t$ and $z_{om} = 0.13 h_t$. The universal functions $\Psi_m(\xi)$ and $\Psi_h(\xi)$ can be determined by following Brutsaert (1982) and Hu et al (1994).

(f). Surface resistance r_s

Surface resistance r_s depends on various governing factors, such as solar flux, leaf water potential, ambient temperature, ambient carbon dioxide, vegetation situation, and vapor pressure deficit. According to Dickinson et al (1986), Noilhan and Planton (1989), the expression of r_s is taken to be

$$r_s = \frac{r_{smin}}{LAI} \cdot \frac{1}{I_1 I_2 I_3 I_4} \tag{13}$$

where r_{smin} is the minimum surface resistance, I_1, I_2, I_3, I_4 are fractional conductances. The factor I_1 represents the influence of the photosynthetic active radiation, it is given by:

$$I_1 = \frac{(r_{smin}/r_{smax}) + f}{1 + f} \quad \text{with} \quad f = 0.55 \frac{Rg}{Rg_l} \frac{2}{LAI} \tag{14}$$

where r_{smax} is the maximum surface resistance, Rg the incoming solar radiation, and Rg_l is a limited value of 30 w/m^2 for a forest and of 100 w/m^2 for a crop. The factor I_2 measures the effects of moisture stress, which is computed by:

$$I_2 = \frac{w_2 - w_{wilt}}{w_{cr} - w_{wilt}} \quad \text{and} \quad 0 \leq I_2 \leq 1 \tag{15}$$

where w_2, w_{wilt}, w_{cr} are the bulk soil moisture, wilting point moisture, and critical moisture respectively. The factors I_3 is about the influence of vapor pressure deficit of the air, it is expressed as:

$$I_3 = 1 - \alpha \, (q_{sat}(T_a) - q_a) \tag{16}$$

where α is a empirical parameter. I_4 represents the effect of the ambient temperature, it is set to:

$$I_4 = 1.0 - 0.0016 \times (298.0 - T_a)^2 \tag{17}$$

The parameters applied in above equtions are either determined by observations and experiments or referred from Noilhan and Planton (1989) and Wu (1994).

3. MODEL VALIDATION AND DISCUSSION

In order to verify the present SPAC model and test its accuracy, field observation data obtained in a winter wheat field in Yucheng (36.98°N, 116.65°E) in northern China (Wu, 1994) are utilized. The observation was started at 0700 local standard time (LST) in April 23 and finished at 0800 LST April 27, 1992. A lot of items were observed or measured, including soil temperature, soil moisture, evapotranspiration, vegetation parameters, and meteorological data. Meanwhile, parameters in the SPAC model are specified in the laboratory, such as soil water conductivity, soil water characteristic curve, soil water capacity, soil water volumetric heat capacity etc.. Fig.1 illustrates the observation of the wheat height and leaf area index. Fig.2 and Fig.3 show some meteorological observations, being net radiation, water vapor pressure, air temperature, and wind velocity, which observed at referent height, 2 meter above the ground surface.
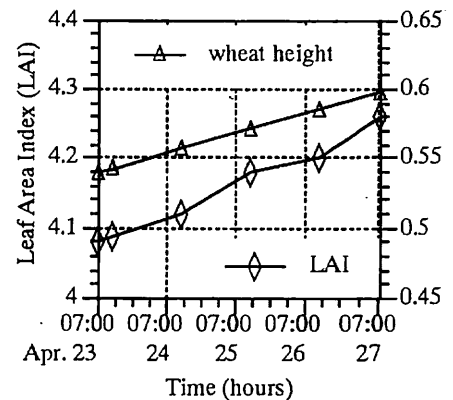
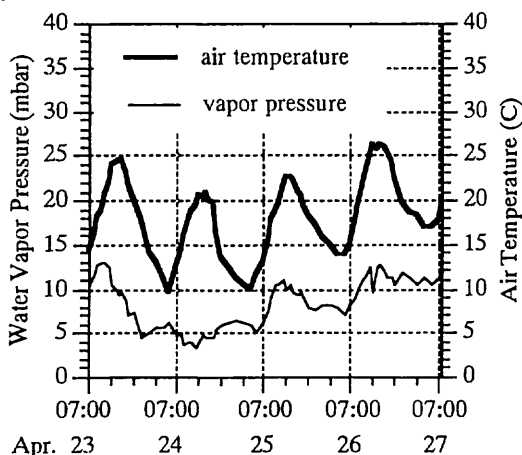Fig.1 Observations of leaf area index and wheat height

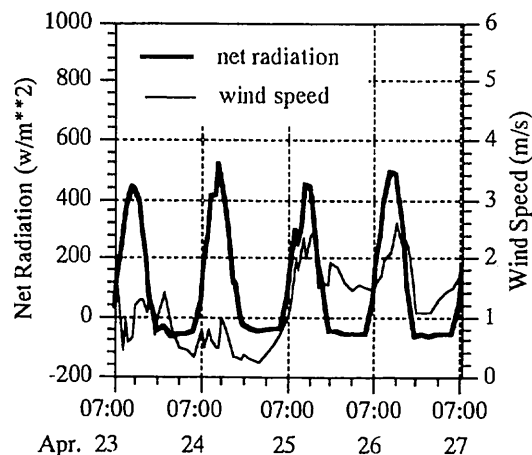Fig.2 Observations of water vepor pressure and air temperature

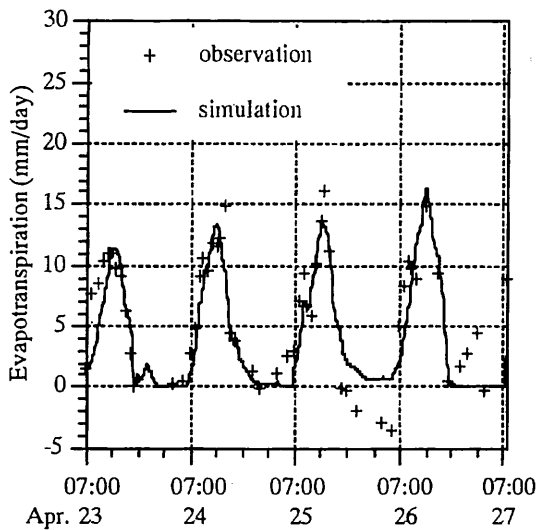Fig.3 Observations of net radiation and wind speed

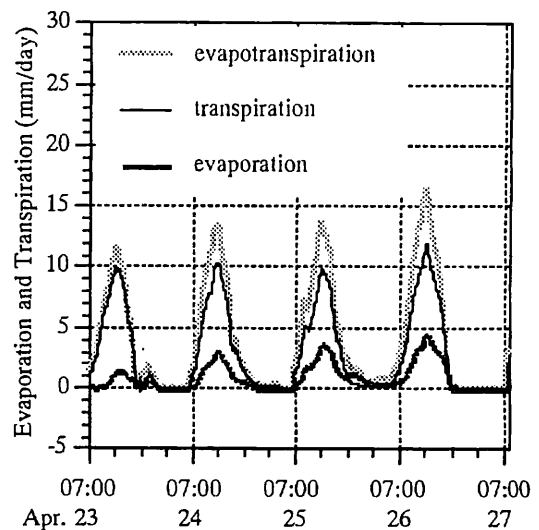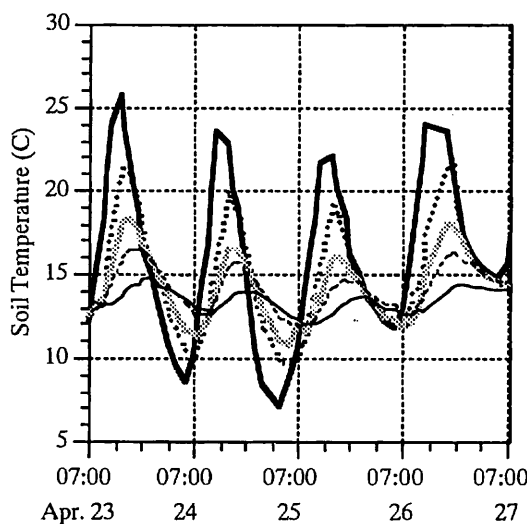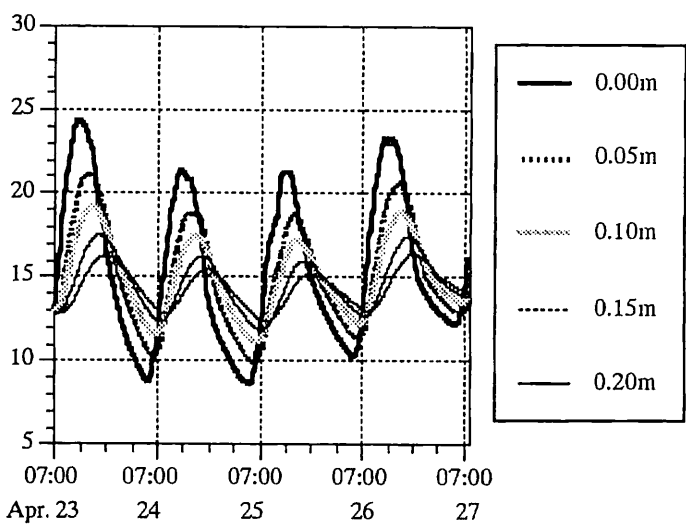Fig.4 Comparison of evapotranspiration

Fig.5 Components in evapotranspiration

(a) Observations

(b) Simulations

Fig.6 Observations and simulations of soil temperatures in
depths of 0.00m, 0.05m, 0.10m, 0.15m, 0.20m

The SPAC model described previously was run with the observed initial and boundary conditions. The meteorological input data are net radiation, water vapor pressure, air temperature, and wind velocity at 2 m above the ground, which are shown in Fig.2 and Fig.3. Fig.4 shows comparison between the simulated evapotranspiration results and the observed data as a function of time. Considering the difficulty of the estimation of the evapotranspiration in such a complex situation, the calculation results are rather good, the biggest deviation being only about 20%. The detail about the evapotranspiration is shown in Fig.5, where the variation of components in the evapotranspiration, evaporation and transpiration, is given. In the

Fig.7 Ground Surface Energy Budget

present case, the transpiration is the dominant factor and contributes to the whole evapotranspiration about 60% or more. Fig.6 shows the comparison of the soil temperatures at different depths, 0.00 m, 0.05 m, 0,10 m, 0.15 m, 0.20 m, in cases of simulation and observation, respectively. The
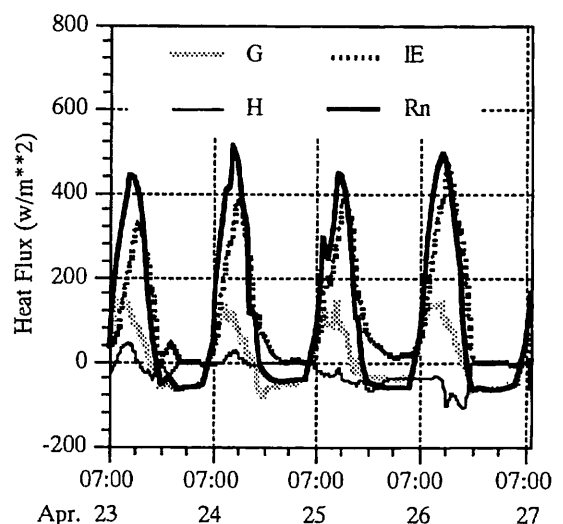
simulated soil temperatures demonstrate fair agreement with the observations, the biggest difference being about 3 degrees. The ground surface energy balance is shown in Fig.7, where R_n is the net radiation, G is the heat flux, lE and H are the latent and sensible heat flux respectively. Most parts of the incoming solar energy are consumed by latent heat, that means consumed by moisture flux. In general, good agreements are obtained between the simulated results and observed ones, thus the present model is verified.

4. SUMMARY AND REMARKS

In this paper, a coupled full-interacting physical SPAC model to describe the dynamic aspects of the moisture and heat transfer in soil, vegetation, and atmosphere is developed. A vegetation model is employed to describe the vegetation as simply as possible, but preserving the essential characteristics of the botanical activities of vegetation. Transpiration is controlled by surface resistance, while the intercepted water of rainfall and dew evaporate at the potential rate. Soil liquid water flux and water vapor flux as well as soil heat flux are taken into account. Only four atmospheric input data are required in the model, they are net radiation, wind speed, vapor pressure, air temperature, which are all regularly observed at meteorological observation stations, so that the present model is an application-oriented model. A field observation conducted in Yucheng in northern China is utilized to verify the model. The next step of the study is to extend the model from lower atmospheric boundary layer to the Ekman layer and to apply the model to macro-scale problems.

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