

A Six-Layer SVAT Model for Energy and Mass Transfer and Its Application to a Spruce(*Picea abies* [L].Karst) Forest in Central Germany.¹

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독일가문비나무(*Picea abies* [L].Karst)林에서의 Energy와 물질循環에 對한 SLODSVAT(Six-Layer One-Dimensional Soil-Vegetation-Atmosphere-Transfer) 모델과 그 適用¹

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SUMMARY

The SLODSVAT consists of interrelated submodels that simulate : the transfer of radiation, water vapour, sensible heat, carbon dioxide and momentum in two canopy layers determined by environmental conditions and ecophysiological properties of the vegetation ; uptake and storage of water in the "root-stem-leaf" system of plants ; interception of rainfall by the canopy layers and infiltration and storage of rain water in the four soil layers.

A comparison of the results of modeling experiments and field micro-climatic observations in a spruce forest(*Picea abies* [L].Karst) in the Solling hills(Germany) shows, that the SLODSVAT can describe and simulate the short-term(diurnal) as well as the long-term(seasonal) variability of water vapour and sensible heat fluxes adequately to natural processes under different environmental conditions. It proves that it is possible to estimate and predict the transpiration and evapotranspiration rates for spruce forest ecosystems on the patch and landscape scales for one vegetation period, if certain meteorological, botanical and hydrological information for the structure of the atmospheric boundary layer, the canopy and the soil are available.

Key words : six-layer SVAT model, heat, water vapour, carbon dioxide, *Picea abies* [L].Karst

要 約

SLODSVAT 모델은 (1)식생의 환경 조건과 생태 생리학적 특징에 의해 결정된 두개 수관층에서의 복사, 수분증발, 열, 이산화탄소 및 바람(momentum) 등의 이동과, (2)식물의 뿌리, 줄기, 잎으로 이어지는 수분의 흡수와 저장 및, (3)수관에 의한 강우의 차단, 그리고 토양에 의한 강우의 저장과 유하 등을 Simulation한 상호관련된 몇 개의 하위 모델들로 구성되어 있다.

본 연구에서는 독일 중부에 위치한 Solling지방의 독일가문비림(*Picea abies* L Karst)을 대상으로 미기후 관측 결과와 모델링에 의한 결과를 서로 비교해 본 바, SLODSVAT는 서로 다른 환경 조건

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하에서 수분증발과 열 흐름의 계절적 변화 뿐만 아니라 일변화도 자연적 과정에 맞게 적절히 설명할 수 있을 수 있었고, 또한 대기, 임관 및 토양 구조에 대한 기상학적, 식물학적, 수문학적 자료들이 유용하다면 독일가문비림 생태계에 대한 증산과 증발산의 비를 평가하고 예측함이 가능함을 알 수 있었다.

INTRODUCTION

Soil-Vegetation-Atmosphere Transfer(SVAT) models are main tools for mathematical representation of the critical processes controlling the energy, water, and carbon transfer among soil, vegetation and atmosphere. All these models use approximations for the natural reality and include many simplifications of the real processes and of their dependencies on the various characteristics and processes.

Most of the models for energy and mass transfer in a vegetation canopy treat the canopy as a single horizontal layer("Big leaf models") or as several closely interacting layers through which pass vertical fluxes of radiation, momentum, sensible and latent heat determined by vertical differences of the relevant potentials and by quantities specifying the exchange properties.

Obviously, different scale models require different degrees of details to describe land-atmosphere interface. Complex two- and three-dimensional multi-layer SVAT models can provide a much more realistic description of land surface properties and a much greater precision for particular vegetation sites than one-dimensional one- or two-layer models. However, the serious problems of their practical application, first of all for modelling processes of energy and mass transfer in landscape and regional scales, are that complex SVAT models are much more demanding in detailed, usually not available, information about the vegetation canopy and the soil structure(Geyer and Jarvis, 1991). Therefore, the developing of not over-complex SVAT models as one of main goals of the modern researches of processes of ground surface and atmosphere interaction for realistic representation of natural processes at the vegetation-atmosphere interface using the some essential input parameters obtained from generally available data including remote sensing(Cienciala et al., 1994). Obviously, each developed SVAT

model must be tested using reliable field data.

The main aim of this paper is to describe the Six-Layer One-Dimensional SVAT model(SLOD-SVAT) that has been developed in order to estimate surface-atmosphere heat(H), water vapour(LE) and carbon dioxide(F) fluxes between a plant canopy and the atmosphere in patch and landscape oriented scales(Oltchev and Stavisky, 1990, Oltchev, 1992). In contrast to other models the SLODSVAT allows to dynamically couple stomatal functioning and CO_2 assimilation of plant canopy layers with the microclimate of the atmospheric boundary layer, with the canopy architecture and the canopy and soil hydrology. It enables to accurately predict and interpret the response of a plant canopy on environmental stresses.

The SLODSVAT has been applied to a quasi-homogeneous stand of spruce trees(*Picea abies* [L.]Karst) in Solling mountains(Central Germany) for the purpose to study the processes of interaction of a spruce forest and the atmosphere on a local scale and to determine the role of environmental factors and ecophysiological properties of spruce trees to regulate and control the CO_2 exchange and the simultaneous loss of water through their stomata.

The first section of this paper outlines the structure of the developed SVAT model and includes the main approximations and governing equations for energy and water budgets in the plant canopy and the soil.

In the second section the results of model simulations are compared with field measurements in a spruce forest in the Solling. A particular attention is given to the parametrisation of the response of needle stomatal conductance to variation of environmental conditions. The predicted diurnal trends of sensible and latent heat fluxes are compared with results of field measurements in spruce forest in Solling for three 2 day representative periods during June-August 1994. These selected periods provided a variety of

environmental conditions including clear as well as partly cloudy and rainy weather. For these periods the sensitivity of the transpiration rate reacts to changing the values of model input parameters is estimated.

MATERIAL AND METHODS

1. Model description

The SLODSVAT consists of interrelated sub-models which simulate the following processes :

- radiation transfer(visible, near infrared and thermal radiation) in the plant canopy ;
- aerodynamic transfer of water vapour, sensible heat, carbon dioxide and momentum between two canopy layers and some reference height in the atmospheric boundary layer ;
- interception of rainfall by the plant canopy and infiltration, storage and drainage of rain water in four soil layers ;
- uptake and storage of water in the "root - stem - leaf" system of the plants governed by the soil, plant and leaf water potentials ;
- transpiration and photosynthesis of two canopy layers determined by the micro climate of the atmospheric boundary layer, the soil and plant water status and the ecophysiological properties of the vegetation.

The transfer pathways for sensible heat, water vapour and carbon dioxide between vegetation and the atmosphere are schematically presented in Fig. 1.

The model boundary conditions at some refer-

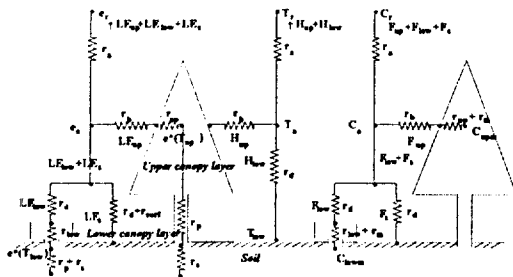


Fig. 1. The transfer pathways for heat, water vapour and carbon dioxide in a plant canopy(indexes *up*, *low*, *s* correspond to the upper and lower canopy layer and to the soil, respectively).

ence height above the plant canopy are measured or predicted values for air temperature(*T_a*), water vapour pressure(*e_a*), concentration of carbon dioxide(*C_a*), wind speed(*u*), incoming solar radiation(*F₀(λ)*) and intensity of precipitation(*P*). At the bottom of the lowest soil layer the SLODSVAT assumes steady-state conditions for temperature and soil moisture.

The SLODSVAT requires the specification of morphological structure and ecophysiological and optical parameters of leaves for each canopy layers, morphological and optical parameters of the soil.

1.1 Microclimate submodel

Microclimatological processes considered here include the radiation transfer in the plant canopy, canopy and soil surface energy budgets, the turbulent vertical transfer of momentum, sensible heat, water vapour and carbon dioxide between the two canopy layers and the atmosphere.

1.1.1 Radiation transfer in plant canopy

The description of radiation transfer in SLODSVAT is based on an idealized structure of the plant canopy as two layers of horizontally homogeneous and optically anisotropic turbid medium and the two-stream approximation. Let us follow this approximation and write the general system of differential equations for a canopy with definite leaf angle distribution as(Sellers et al., 1986) :

$$-\bar{\mu} \cdot \frac{dI_{\downarrow}}{dL} + (1 - (1 - \beta) \cdot \omega) \cdot I_{\downarrow} - \omega \cdot \beta \cdot I_{\uparrow} - \omega \cdot \bar{\mu} \cdot K \cdot \beta_0 \cdot e^{-KL}, \tag{1}$$

$$-\bar{\mu} \cdot \frac{dI_{\uparrow}}{dL} + (1 - (1 - \beta) \cdot \omega) \cdot I_{\uparrow} - \omega \cdot \beta \cdot I_{\downarrow} - \omega \cdot \bar{\mu} \cdot K \cdot (1 - \beta_0) \cdot e^{-KL},$$

where :

I_↑, *I_↓* are upward and downward diffuse radiation fluxes, respectively, normalised by the incident flux ; *μ* is cosine of solar zenith angle ; *K*=*G(μ)*/*μ* is optical depth of the direct solar beams per unit leaf area ; *G(μ)* is the relative projected area of leaf elements in direction *μ* ; *μ̄* is averaged inverse diffuse optical depth per unit leaf area ; *β*, *β₀* are up scatter parameters for the diffuse and direct solar radiation, respectively ; *ω* is scattering coefficient of phyto-elements ; *L* is

projected plant area index in $m^2 m^{-2}$.

The short-wave radiation absorbed by the two layers of the canopy including the soil surface is given by

$$\begin{aligned}
 F_{up}(\Delta\lambda) &= V_{up} \cdot (1 - I_{up} - I_{low}^{up} \cdot (1 - A_d(\Delta\lambda))) \\
 &\quad - e^{-KL_{up}} \cdot (1 - A_b(\lambda)) \cdot F_0(\Delta\lambda) \\
 F_{low}(\Delta\lambda) &= (1 - V_{up}) \cdot (1 - A_d(\Delta\lambda)) + V_{up} \cdot \\
 &\quad (I_{low}^{up} \cdot (1 - A_d(\Delta\lambda)) + \\
 &\quad e^{-KL_{low}} \cdot (1 - A_d(\Delta\lambda))) \cdot F_0(\Delta\lambda)
 \end{aligned} \tag{2}$$

where :

$F_0(\Delta\lambda)$ is the incident solar radiation of wavelength interval $\Delta\lambda$; $F_{up}(\Delta\lambda)$ is solar radiation absorbed by upper layer of the canopy ; $F_{low}(\Delta\lambda)$ is solar radiation absorbed by lower layer of the canopy and soil surface ; V_{up} is fractional area covered by upper layer of the canopy ; I_{up} , I_{low}^{up} are upward and downward normalised diffuse fluxes for upper layer of the canopy ; $e^{-KL_{up}}$ is the direct radiation flux penetrating the canopy ; L_{up} is the local projected plant area index of the upper layer of the canopy ; $A_b(\Delta\lambda)$, $A_d(\Delta\lambda)$ are the soil albedo values for direct and diffuse solar radiation.

The long wave radiation balance of two layers of canopy under clear and cloudy sky conditions are expressed in term of temperatures of the canopy layers and the estimated down welling atmospheric infrared flux(Kondratyev, 1969, Smith et al., 1993, Sellers et al., 1986) :

$$\begin{aligned}
 F_{up}(IR) &= V_{up} \cdot \sigma_s \cdot (\epsilon_c \cdot T_{low}^4 + \epsilon_a \cdot T_a^4 \cdot d_1 \cdot \\
 &\quad (e_a / T_a)^{d_2} \cdot (1 + c' \cdot N) - 2 \cdot \epsilon_c \cdot T_{up}^4) \\
 F_{low}(IR) &= (1 - V_{up}) \cdot \epsilon_a \cdot \sigma_s \cdot T_a^4 \cdot d_1 \cdot (e_a / T_a)^{d_2} \cdot \\
 &\quad (1 + c' \cdot N) + V_{up} \cdot \epsilon_c \cdot \sigma_s \cdot T_{up}^4 \\
 &\quad - \epsilon_c \cdot \sigma_s \cdot T_{low}^4
 \end{aligned} \tag{3}$$

where :

T_{up} , T_{low} are temperature of the upper and lower canopy layer in K ; T_a is the air temperature at reference height in K ; σ_s is Stefan-Boltzmann constant ; ϵ_a , ϵ_c are apparent emissivity of the atmosphere and the canopy ; d_1 , d_2 , c' are empirical constants and N is the amount of cloud cover.

Finally, the net radiation fluxes(Rn_{up} , Rn_{low}) are calculated as the sum of short-wave and

long-wave radiation absorbed by canopy layers :

$$\begin{aligned}
 Rn_{up} &= F_{up}(\Delta\lambda) + F_{up}(IR) \\
 Rn_{low} &= F_{low}(\Delta\lambda) - F_{low}(IR)
 \end{aligned} \tag{4}$$

1.1.2 Canopy and ground surface-soil energy budgets.

The radiation energy absorbed by the canopy and the soil is partitioned between latent and sensible heat fluxes, storage of heat in the two canopy and four soil layers. The temperature of each canopy layer(T_{up} , T_{low}) can be estimated by the iteration method for energy balance equations which can be written in generalised forms as

$$\begin{aligned}
 C_{up} \cdot \partial T_{up} / \partial t - Rn_{up} - H_{up} - LE_{up} \\
 C_{low} \cdot \partial T_{low} / \partial t - Rn_{low} - H_{low} - LE_{low} - G_s
 \end{aligned} \tag{5}$$

where :

C_{up} , C_{low} are heat capacities in $J m^{-2} K^{-1}$; H_{up} , H_{low} are sensible heat fluxes in $W m^{-2}$; LE_{up} , LE_{low} are latent heat fluxes in $W m^{-2}$ for upper and lower canopy layers, respectively ; G_s is soil heat flux in $W m^{-2}$.

The partitioning of the absorbed radiation energy strongly depends on environmental and canopy conditions. The LE is driven by the gradient of water pressure between air within stomatal cavities and surrounded air. Model assumes that air in stomatal cavities is saturated, and the temperature of this air is equivalent to leaf surface temperature. The H is driven by the difference of potential temperatures of plant surface and canopy air. Using the resistance analogue the equation for H_{up} , H_{low} and LE_{up} , LE_{low} can be written as follows(Sellers et al., 1986) :

$$\begin{aligned}
 H_{up} &= \rho \cdot c_p \cdot \frac{m \cdot (T_{up} - T_a)}{r_b} \\
 LE_{up} &= \frac{\rho \cdot c_p}{\gamma} \cdot m \cdot (e^*(T_{up}) - e_a) \cdot \left(\frac{N_{up}}{r_b} - \frac{1 - N_{up}}{r_b + r_{up}} \right) \\
 H_{low} &= \rho \cdot c_p \cdot \frac{m \cdot (T_{low} - T_a)}{r_d} \\
 LE_{low} &= \frac{\rho \cdot c_p}{\gamma} \cdot (e^*(T_{low}) - e_a) \cdot \left(V_{low} \cdot \left(\frac{N_{low}}{r_b} - \frac{1 - N_{low}}{r_b + r_{low}} \right) + \frac{f_s \cdot (1 - V_{low})}{r_b + r_{surf}} \right)
 \end{aligned} \tag{6}$$

where :

r_b and r_d are bulk boundary layer resistance and aerodynamic resistance between the lower canopy layer and some effective height in the

upper canopy layer in $s\ m^{-1}$, respectively; V_{low} is the fractional cover of lower canopy layer (ground surface layer); N_{up} , N_{low} are fraction of wetted leaves in upper and lower canopy layers, respectively; f_s is a factor for air humidity; m is the ratio of total and projected plant areas for the upper canopy layer.

The total sensible and latent heat fluxes (H_r , LE_r) at some reference height in the boundary layer are given by

$$\begin{aligned} H_r &= H_{up} + H_{low} = \rho \cdot c_p \cdot (T_a - T_r) / r_a \\ LE_r &= LE_{up} + LE_{low} = \rho \cdot c_p \cdot (e_a - e_r) / (\gamma \cdot r_a) \end{aligned} \quad (7)$$

where :

r_a is aerodynamic resistance between canopy air space and reference height in atmospheric boundary layer in $s\ m^{-1}$.

1.1.3 Turbulent transfer and aerodynamic resistances.

The modelling of the vertical turbulent regime above and within the plant canopy and calculation of aerodynamic resistances are based on the numerical solution of the system of hydrodynamic and semiempirical equations with following approaches :

- the canopy is considered as a continuous medium ;
- the phytoelements are distributed randomly in canopy layers ;
- the behaviour of the individual eddies is not considered.

Equation of motion within the horizontally homogeneous canopy is :

$$\frac{1}{\rho} \frac{d\tau}{dz} = C_d \cdot S \cdot U^2, \quad (8)$$

where :

S is plant area density in $m^2\ m^{-3}$, ρ is air density in $kg\ m^{-3}$, τ is shearing stress in $kg\ m^{-1}\ s^{-2}$, C_d is drag coefficient and U is the horizontal wind speed ;

or

$$\frac{d}{dz} k(z) \frac{dU}{dz} = C_d \cdot S \cdot U^2 \quad (9)$$

where :

$k(z)$ is the vertical turbulent exchange coefficient of momentum in $m^2\ s^{-1}$.

To solve the equation of motion Monin and

Jaglom(1967) suggested to use the balance equation for the turbulent kinetic energy :

$$\begin{aligned} k(z) \cdot \left(\frac{dU}{dz} \right)^2 + a_b \cdot \frac{d}{dz} k(z) \frac{db}{dz} \\ = \frac{C \cdot b^2}{k(z)} - C_d \cdot S \cdot U^2 \end{aligned} \quad (10)$$

where :

C is constant ($C=0.046$) ;

b is kinetic energy of fluctuations,

$$b = (\bar{U}^2 + \bar{V}^2 + \bar{W}^2) / 2 ;$$

$$a_b = k_b(z) / k(z) = 0.73 ;$$

$k_b(z)$ is the vertical turbulent exchange coefficient for kinetic energy in $m^2\ s^{-1}$;

$C \cdot b^2 / k(z)$ is the dissipation rate of turbulent kinetic energy to thermal energy.

The method of closure for a system of two equations with four unknown variables is based on the hypothesis about the self-similarity of the turbulence for kinetic energy (b) and the mixing length(l) (Dubov et al., 1978, Boyko and Sirotenko, 1985, Mengulin et al., 1989) :

$$k(z) = C^{1/4} \cdot l \cdot b^{1/2} ; \quad l = \lambda \cdot z / \{ 1 + 2.5 \cdot z \cdot (C_d \cdot S / h)^{1/2} \}$$

where :

h is averaged height of the plant canopy in m.

The modelled profiles of $U(z)$ and $k(z)$ can be used to obtain aerodynamic resistances r_a , r_b and r_d .

The aerodynamic resistance for momentum, heat, water vapour and carbon dioxide transfer between the some reference height in atmospheric boundary layer above uniform surface (z_R) and the effective height for the sink in upper layer of the canopy ($z_S = d + z_0$) at neutral atmospheric conditions r_{a0} is defined in the SLODSVAT as

$$r_{a0} = \int_{z_R}^{z_S} dz / k(z) \quad (11)$$

To take into account the influence of atmospheric thermal stability on the turbulent transfer the model used a diabatic stability function (F) which according to Thom(1986) and Brutsaert (1982) can be written as

$$\begin{aligned} F &= (1 - 5.2 Ri)^{-2} \quad \text{for stable conditions} \\ F &= (1 - 16 Ri)^{3/4} \quad \text{for unstable conditions} \end{aligned}$$

Finally, the equation for r_a can be written as

$$r_a = r_{ab} \cdot F, \tag{12}$$

For the estimation of effective values of temperature, water vapour pressure and carbon dioxide concentration in air surrounding foliage of upper canopy layer, it is necessary to find out the mean boundary layer resistance r_b between foliage surface and surrounding air space within the upper canopy layer, which is a function of local wind speed and geometrical size of the surface (Brutsaert, 1982, Monteith and Unsworth, 1990), and aerodynamic resistance between the plants of lower canopy layer and surrounding air space within the upper canopy layer (r_d). The SLOD-SVAT follows Choudhury and Monteith(1988) and parameterises the boundary layer resistance for exchange of some substance between a single leaf and surrounded air($r_{a, nl}$) as :

$$1/r_{a, nl} = a \cdot (U(z)/w)^{1.2} \tag{13}$$

where :

a is empirical constant ; w is leaf width in m ; $U(z)$ is local wind speed at height z in $m\ s^{-1}$.

For canopy layer consisting of many sublayers with a local PPAI(dL), the mean boundary layer resistance \bar{r}_b can be determined in general form as :

$$\frac{1}{\bar{r}_b} = \int_0^{L_{int}} \frac{dL_{int}}{r_{bi}} \Big/ \int_0^{L_{int}} dL_{int} \tag{14}$$

where :

L_{int} is the integrated PPAI estimated downward from the top of the canopy(L_{int} =PPAI at bottom of the canopy layer) in $m^2\ m^{-2}$.

The mean resistance per unit ground area is written as :

$$r_b = \bar{r}_b / L \tag{15}$$

The aerodynamic resistance between the plants of lower canopy layer and surrounding air within upper canopy layer under neutral conditions of the atmosphere can be formally defined as(Sellers et al., 1986) :

$$r_{ab} = \int_z^{z_1} dz / k(z) \tag{16}$$

To take into account the effects of atmospheric non-neutrality within a plant canopy the equation for r_b can be modified as :

$$r_d = r_{db} \cdot F_d \tag{17}$$

where :

For taking into account the effects of atmospheric non neutrality the equation for r_{db} can be modified as :

$$r_{db} = r_{db} \cdot F_d \tag{18}$$

where :

F_d is a diabatic stability function for momentum transfer between lower(ground surface) and upper canopy layers.

1.2 Interception of precipitation.

The interception of precipitation by canopy layers is determined by an adaptation of the parametrisation describing the exponential attenuation of radiation when the flux is vertical and the leaves are black(Sellers et al., 1986). The rate of interception and outflow of intercepted water to the ground for the upper and lower canopy layers are given by

$$P_{up} = P \cdot (1 - e^{-K_{up}L_{up}}) \cdot V_{up} ; \tag{19}$$

$$P_{low} = (P - P_{up} + U_{up}) \cdot (1 - e^{-K_{low}L_{low}}) \cdot V_{low} ;$$

$$U_{up} = \begin{cases} -0 & \text{when } M_{up} < S_{up} \\ -P_{up} & \text{when } M_{up} \geq S_{up} \end{cases} \tag{20}$$

$$U_{low} = \begin{cases} -0 & \text{when } M_{low} < S_{low} \\ -P_{low} & \text{when } M_{low} \geq S_{low} \end{cases}$$

where :

P_{up} , P_{low} are rate of precipitation interception in $m\ s^{-1}$; U_{up} , U_{low} are rate of outflow of intercepted water $m\ s^{-1}$; M_{up} , M_{low} are water interception capacity for upper and lower canopy layers in m, ; S_{up} , S_{low} are maximum values of M_{up} and M_{low} in m ; L_{up} , L_{low} are projected leaf area for upper and lower canopy layers in $m^2\ m^{-2}$, respectively.

When there is intercepted water on the leaf surface the transpiration is assumed to continue from those parts of leaves which are still dry.

1.3 Soil and plant water dynamics.

The vertical water transport in four soil layers is modelled on the basis of Darcy's law(Brutsaert, 1982, Sellers et al., 1986). For partly saturated

soil it can be written as

$$Q_{i,i+1} = -\bar{k} \cdot \left(2 \cdot \frac{\Psi_i - \Psi_{i+1}}{D_i - D_{i+1}} - 1 \right) \quad (21)$$

where :

$\bar{k} = (D_i k_i + D_{i+1} k_{i+1}) / (D_i + D_{i+1})$ is effective hydraulic conductivity between layers i and $i+1$ in m s^{-1} ; $\Psi_{i,i+1}$ are soil water potentials in m; $D_{i,i+1}$ are depth of i th and $i+1$ th soil layers in m, respectively.

Soil hydraulic conductivity k is dependent on soil water content and texture. According to Campbell(1974) k is modelled in the i th soil layer for unsaturated conditions as

$$k_i = k_{si} \cdot (\theta_i / \theta_{si})^{2B+3} \quad (22)$$

where :

k_{si} is saturated hydraulic conductivity in m s^{-1} ; B_i is empirical constant depending on texture of i th soil layer; θ_i , θ_{si} are volumetric and saturated volumetric soil moistures in layer i , respectively.

The governing generalised equation for water budget in soil layers is given by

$$\frac{\partial W_i}{\partial t} = \frac{(Q_{i-1,i} - Q_{i,i+1} - (E_i + E_{si}) / \rho_w)}{\theta_{si} \cdot D_i} \quad (23)$$

where :

$W_i = \theta_i / \theta_{si}$ is soil moisture in i th soil layer; $Q_{i-1,i}$, $Q_{i,i+1}$ are water flow between $i-1$ and i , and between i and $i+1$ soil layers, respectively in m s^{-1} ; $E_i = E_{iup} + E_{ilow}$ is water uptake by roots for the upper and lower canopy layers in $\text{kg m}^{-1} \text{s}^{-1}$, E_{si} is direct evaporation of soil water into the atmosphere in $\text{kg m}^{-1} \text{s}^{-1}$; ρ_w is water density in kg m^{-3} .

For upper soil layer $Q_{i-1,i}$ is equal to the effective precipitation rate on the soil surface P_0 that can be defined as(Sellers et al., 1986)

$$P_0 = P - (P_{up} + P_{low}) + (U_{up} + U_{low}) \quad (24)$$

The pathway of water from soil to air space within the plant canopy is represented by four resistances : the soil-root($r_{sr \text{ up, low}}$), stem($r_{p \text{ up, low}}$), branch($r_{br \text{ up, low}}$) and leaf stomatal($r_{up, low}$) resistances(Oltchev and Stavisky, 1990). The water uptakes by roots(E_{iup} , E_{ilow}) across the

resistances of the soil-roots(r_{sr}) and the stem(r_p) are given by

$$E_{iup} = \frac{D_i}{Z_{rup}} \cdot \left(\frac{\Psi_i - \Psi_{pup} - z_{Ssp}}{r_{srup} + r_{pup}} \right) \cdot \rho_w \quad (25)$$

$$E_{ilow} = \frac{D_i}{Z_{rlow}} \cdot \left(\frac{\Psi_i - \Psi_{plow} - z_{Sslow}}{r_{sr low} + r_{plow}} \right) \cdot \rho_w$$

where :

$\Psi_{p \text{ up, low}}$ are plant water potentials, determined by available water reservoirs in plants which are supplied through root uptake; $Z_{r \text{ up, low}}$ are root depths; $z_{S \text{ up, low}}$ are effective heights of transpiration sources for upper and lower canopy layers, respectively.

Since in each canopy layer there is only one reservoir of water the leaf water potentials are assumed the same for all leaves in canopy layer. These effective leaf water potentials are extracted by iterative solutions of budget equations for the available plant water :

$$\frac{\partial W_{up}}{\partial t} = \frac{E_{iup} + E_{siup}}{\theta_{sup} \cdot \rho_w} \quad (26)$$

$$\frac{\partial W_{low}}{\partial t} = \frac{E_{ilow} + E_{silow}}{\theta_{slow} \cdot \rho_w}$$

where :

θ_{sup} are volumetric and saturated volumetric soil moistures in the canopy layers.

For the lower canopy layer the root water uptake(E_{rlow}) is equal to transpiration rate(E_{low}) in $\text{kg m}^{-1} \text{s}^{-1}$.

1.4 Canopy stomatal resistance.

The leaf stomatal resistances($r_{up, low}$) depend on the incoming photosynthetically active radiation (PAR), the leaf temperatures($T_{up, low}$), the atmospheric water vapour deficit(D_a) and the leaf water potentials($\Psi_{up, low}$) :

$$\frac{1}{r_{up}} = \frac{1}{r_{up \text{ MIN}}} \cdot f_1(\text{PAR}) \cdot f_2(T_{up}) \cdot f_3(D_a) \cdot f_4(\Psi_{up}) \quad (27)$$

$$\frac{1}{r_{low}} = \frac{1}{r_{low \text{ MIN}}} \cdot f_1(\text{PAR}) \cdot f_2(T_{low}) \cdot f_3(D_a) \cdot f_4(\Psi_{low})$$

where :

$r_{up \text{ MIN}}$, $r_{low \text{ MIN}}$ are minimal stomatal resistances; $f_1(\text{PAR}) \cdot f_2(T_i) \cdot f_3(D_a) \cdot f_4(\Psi_i)$ are factors introduced by Jarvis(1976) and determining the

influence of T_i , D_a , ψ_i and incoming PAR on leaf stomatal resistance(r_l). The factors are limited to the range from 0(the transpiration totally suppressed by adverse environmental conditions) to 1(under optimal conditions).

The light response function of $r_{lup, low}$ is expressed by a factor $f_l(PAR)$ that can be defined as :

$$f_l(PAR) = 1 - \exp(-\beta_{sl} \cdot PAR) \quad (28)$$

where :

β_{sl} is an empirical parameter determining the slope of the light response curve at $PAR \rightarrow 0$.

The stomata will cease functioning at temperatures of freezing($T < 0^\circ C$) and of rapid protein denaturation($T > 35^\circ C$). Following Jarvis(1976) the factor $f_2(T_i)$ describing the influence of leaf temperature on r_l can be expressed as :

$$f_2(T_i) = \frac{(T_i - T_{lopt}) \cdot (T_{lmax} - T_i)^{M_1}}{(T_{lopt} - T_{imin}) \cdot (T_{lmax} - T_{lopt})^{M_1}} \quad (29)$$

$$h_1 = (T_{lmax} - T_{lopt}) / (T_{lopt} - T_{imin})$$

where :

$T_{l opt, l min, l max}$ are optimum and lower and upper temperature limits for stomatal conductivity, respectively.

The stomatal conductance of many plant species decreases as air water vapour deficit increases (Schulze and Hall, 1982). The role of air water vapour deficit on stomatal regulation is complicated due to feedback effects and interdependencies among the transpiration, water vapour deficit of air and needle temperature. The humidity control on stomatal functioning is simultaneously changed by temperature feedback. A reduction of transpiration can lead to an increase of the needle temperature and a saturation water vapour pressure in the stomatal cavities. Following Lohammar et al.(1980) the form of the factor used to account the effects of water vapour deficit $f_3(D_a)$ is given by :

$$f_3(D_a) = 1 / (1 + \alpha \cdot D_a) \quad (30)$$

where :

α is an empirical constant.

The factor $f_4(\psi_i)$ describing the influence of ψ_i on r_l is given by Sellers et al.(1989)

$$f_4(\psi_i) = \begin{cases} 1, & \text{then } \psi_i < \psi_{c1} \\ (\psi_i - \psi_{c2}) / (\psi_{c1} - \psi_{c2}), & \text{then } \psi_{c1} \leq \psi_i \leq \psi_{c2} \\ 0, & \text{then } \psi_i > \psi_{c2} \end{cases} \quad (31)$$

where :

$\psi_{c1, c2}$ are the values of ψ_i when the stomata start to close and when they are completely closed in m, respectively.

The integral stomatal resistances of the canopy layers($1/r_{up}$, $1/r_{low}$) to the transport of water vapour into the atmosphere are assumed to be equal to the effect of all stomata.

$$r_{up} = \int_0^{L_{up}} dL_{up} / r_{up} \quad (32)$$

$$r_{low} = \int_0^{L_{low}} dL_{low} / r_{low}$$

where :

$L_{up, l}$ and $L_{low, l}$ are the leaf area indexes for upper and lower canopy layers.

1.5 Canopy photosynthesis and soil respiration.

Net photosynthesis(F_c) for two canopy layers is calculated in a similar way as LE . The resistance of the carbon dioxide transfer is however extended by an additional mesophyll resistance (r_m) for the CO_2 transfer between the substomatal cavity and the site of fixation(the equivalent for biochemical resistance of fixation)(Fig. 2). In generalised form the equations for CO_2 fluxes between canopy layers and the atmosphere are given by

$$F_{c up} = m \cdot (C_{up} - C_a) \cdot ((1 - N_{up}) / (r_{bc} - r_{up} + r_{mb})) + F_{c stem} \quad (33)$$

$$F_{c low} = (C_{mlow} - C_a) \cdot ((1 - N_{low}) / (r_{dc} + r_{low} + r_{mlow})) + F_{c soil} + F_{c root up}$$

where :

$C_{m up, m low}$ are the CO_2 concentrations at the intercellulars of upper and lower canopy layers ; C_a is CO_2 concentration at air space of upper canopy layer ; $r_{b, c, d, e}$ are aerodynamic resistances for CO_2 exchange in $s m^{-1}$; $F_{c stem}$, $F_{c soil}$ and $F_{c root up}$ are branch, soil biome and root respiration rate in $mol m^{-2} s^{-1}$, respectively.

The mesophyll resistance(r_m) to CO_2 diffusion is assumed to depend on incoming PAR and on leaf temperature(Lohammar et al., 1980) :

$$1/r_{m up, low} = 1/r_{m min up, low} \cdot f(PAR) \cdot f(T_{l up, low}) \quad (34)$$

where :

$r_{min}^{up, low}$ are minimal value of $r_{m, up, low}$.

Leaf and stem respiration rates($F_{c, l, stem}$) which consist of maintenance and growth respiration are modelled as

$$F_{c, l, stem} = M_{l, stem} \cdot (\varphi_{l, main} + \varphi_{l, gr} \cdot f(T_l)) \quad (35)$$

where :

$M_{l, stem}$ are the dry weight of leaves and plant stems in $kg\ m^{-2}$; $\varphi_{main, gr}$ are maintenance and growth respiration coefficients that correspond to maximal maintenance and growth respiration per unit of dry leaf and stem weight in $mol\ m^{-2}\ s^{-1}$; $f(T_{l, stem})$ are functions describing the dependence of growth respiration on leaf and stem temperatures($T_{l, up, low}$, $T_{stem}(T_{stem} \approx T_{up})$):

$$f(T_{l, stem}) = \begin{cases} a \cdot \exp(b \cdot (T_{l, stem} - T_{ref})); & T_{l, stem} \neq T_{ref} \\ 0; & T_{l, stem} = T_{ref} \end{cases} \quad (36)$$

where :

a, b are empirical parameters; T_{ref} is the reference temperature.

The CO_2 flux from the surface of the soil into the atmosphere is produced mainly by the respiration of soil biota and plant roots. Some CO_2 can be produced chemically by the combination of acid rain with limestone soils. Moreover, the soil pore space taken up by rainwater displaces also some CO_2 (Norman et al., 1992). The SLODSVAT partially follows these approaches and as a first approximation uses the adopted empirical relationship of Norman et al. (1992) to calculate the respiration of soil biota and plant roots in the lower canopy layer :

$$F_{csoil} = F_{csoilMAX} \cdot (W_s - W_{min}) / (W_{max} - W_{min}) \cdot f(T_s) \quad (37)$$

where :

$F_{cs, MAX}$ is a maximal CO_2 soil flux at H_2O field capacity and reference soil temperature($T_{s, ref}$) in $\mu mol\ m^{-2}\ s^{-1}$; $f(T_s) = a_s \cdot \exp(b_s \cdot (T_s - T_{s, ref}))$ represents the influence of soil temperature; W_s is averaged soil moisture; $W_{MIN, MAX}$ are extreme values of W_s .

The respiration of the fine roots($F_{c, root, up}$) of

plants in the upper canopy layer consists of maintenance and growth respirations and is described similar to $F_{c, stem}$ as

$$F_{c, root, up} = M_{root, up} \cdot (\varphi_{r, main} + \varphi_{r, gr} \cdot f(T_s) \cdot f(W_s)) \quad (38)$$

where :

$M_{root, up}$ is the dry weight of roots of plants in the upper canopy layer in $kg\ m^{-1}$; $\varphi_{r, min, r, gr}$ are maintenance and growth respiration coefficients that correspond to maximal maintenance and growth root respiration per unit of dry root weight in $mol\ s^{-1}$; $f(T_s)$, $f(W_s)$ are functions describing the dependencies of growth respiration on temperature and moisture of the soil.

1.6 Soil thermal dynamics.

Over land surface covered with vegetation the daily mean values of soil heat flux(G) is one or two orders of magnitude smaller than major other terms of the energy budget(Brutsaert, 1982). However, over a short period it can be a very important term. It plays important roles not only in energy and mass exchanges between land surface and the atmosphere but also in biochemical and biophysical processes in soil, such as soil respiration, root growth etc.

In the SLODSVAT the soil thermal dynamics are modelled by solving the equation of the thermal conductivity :

$$C_s \frac{\partial T}{\partial t} = - \frac{\partial}{\partial z} \cdot (K_T \cdot \frac{\partial T}{\partial z}) \quad (39)$$

where :

$C_s = \rho_s \cdot c_s$ is the volumetric heat capacity, ρ_s is the density, c_s is specific heat and K_T is the thermal vertical conductivity of the soil.

The volumetric heat capacity C_s is a function of soil texture and soil water content and estimated according to Brutsaert(1982) :

$$C_s = \rho_m \theta_m c_m + \rho_c \theta_c c_c + \rho_w \theta_w c_w + \rho_a \theta_a c_a \quad (40)$$

where :

indexes m, c, w and a correspond to fractions of mineral soil, organic matter, water and air, respectively.

At the soil surface the soil heat flux G_s is given by

$$G_s = -K_T \cdot \partial T / \partial z \quad (4)$$

2. Model calibration and validation.

The developed SVAT model has been applied to a quasi-homogeneous spruce stand (*Picea abies* [L.] Karst) in Solling's mountains (Central Germany) for the purpose to test it using available data of continuous long term micrometeorological and hydrological measurements. This part of paper shortly discusses the results of quantification of leaf stomatal conductance as a function of environmental conditions. The modelled *LE* and *H* compare with results of field measurements for three 2-day representative periods during June - August 1994. Moreover, this part of paper examines how sensitive the transpiration rate reacts to changes of model input parameters.

Tables 1 and 2 include the principal input parameters of the plant canopy and soil used by

the SLODSVAT.

2.1 Experimental site and equipment.

The experimental site is located on large plateau in the Solling's mountains in Central Germany (51° 46' N, 09° 35' E, 505m above sea-level). The plateau is mainly covered by a spruce forest (*Picea abies*) of 31m height, planted in 1884 (Ellenberg et al., 1986). To the south and south-west of the measurement site the spruce forest is relieved by a beech stand (*Fagus sylvatica*) of 24m in height.

The *H* and *LE* above the forest canopy were calculated from profile measurements with Bowen ratio-energy balance method. The psychrometers (THIES, Clima, Germany) for temperature and water vapour pressure measurements were installed on a microclimatological tower at five levels above the forest canopy. The radiation balance was measured at 39m by a Radiometer

Table 1. The principal morphological and optical parameters of the plant canopy used by the SLODSVAT.

Parameters	Symbols	Upper canopy later	Lower canopy layer
<i>Morphological parameters</i>			
Projected plant area index	$L_{n\ u} ; L_{n\ low}$	6.8m ² m ⁻²	1.0m ² m ⁻²
Fractional cover	$V_u ; V_{low}$	0.88	0.30
Leaf angle distribution	-	spherical	spherical
Height of the top	$h_{z\ u} ; h_{z\ low}$	30.0m	0.50m
Height of bottom	$h_{l\ u} ; h_{l\ low}$	1.50m	0.00m
Effective rooting depth	$Z_r\ u ; Z_r\ low$	1.1m	0.2m
Root length density	$D_r\ u ; D_r\ low$	783m	125
<i>Optical parameters</i>			
Leaf(needle) reflection coefficient for PAR	$\rho_{u\ P} ; \rho_{low\ P}$	0.060	0.050
Leaf(needle) reflection coefficient for NIR	$\rho_{u\ N} ; \rho_{low\ N}$	0.340	0.300
Leaf(needle) transmission coefficient for PAR	$\tau_{u\ P} ; \tau_{low\ P}$	0.002	0.020
Leaf(needle) transmission coefficient for NIR	$\tau_{u\ N} ; \tau_{low\ N}$	0.020	0.150
Stem reflection coefficient for PAR	$\rho_{ust\ P} ; \rho_{lowst\ P}$	0.050	0.050
Stem reflection coefficient for NIR	$\rho_{ust\ N} ; \rho_{lowst\ N}$	0.200	0.020

Table 2. The principal hydraulic parameters of soil layers used by the SLODSVAT (According to Clapp and Hornberger(1978) and Benecke (1984)).

Soil layer in m	Texture	$\theta_s (m^3 / m^3)$	$K_s (cm / min)$	$B (-)$	$\Psi_s (cm)$
0.00 - 0.20	Loam	0.451	0.06950	5.39	14.6
0.20 - 0.60	Loam	0.451	0.01750	5.39	14.6
0.60 - 1040	Silt Loam	0.485	0.00350	5.30	56.6
1.40 - 3.00	Loam	0.451	0.00008	5.39	14.6

(Dr. B. Lange, Berlin, Germany). Two pyranometers(Kipp & Zonen CM-11, Netherlands) and two quantum sensors(LI-190SZ, LI-COR, USA) were used to determine the total upward and downward short-wave and photosynthetically active radiation. The needle(twig) stomatal conductance was measured with the Steady-State Porometer(LI-1600, LI-COR, USA).

RESULTS AND DISCUSSION

1. Parameterisation of leaf stomatal conductance functions.

The parameters of the needle(leaf) stomatal conductance(g_{lup}) functions(Eqs. 27-30) were measured over a period of 10 days(24 June-4 July 1994). The g_{lup} (inverse form of the needle stomatal resistance($g_{lup} = 1/r_{lup}$)) was used to avoid high values in the fitting procedure. For a first approximation the g_{lup} functions were parameterised in a generalised form for all needles with different ages and with different sun exposures.

Fig. 2(a-c). shows the results of least-squares approximation for dependencies of maximal g_{lup} ($g_{lup\ max}$) on incoming PAR, on needle temperature and on water vapour deficit in air. An estimation of $g_{lup\ max}$ is based on the well-known method of "Rounding curve". This method, applied to estimate the $g_{lup\ max}$ functions, assumes that the rounding curve drawn around all g_{lup} values and built as a function of some independent variable (PAR, T_l or D_a), could be considered as the $g_{lup\ max}$ function of the corresponding independent variable under optimal conditions for the stomatal functioning. In order to increase the reliability of approximated $g_{lup\ max}$ functions and to exclude possible missing values the rounding curves were derived for g'_{lup} that corresponds to g_{lup} in the 90 percentage point of the cumulative probability distribution function $F(g_{lup})$ calculated for each interval of PAR, T_{lup} , D_a .

In the first approximation the rounded curves were obtained on the basis of analysis of initially measured g_{lup} without preliminary corrections. The second step includes the analysis of corrected values of g_{lup} which have been modified by taking into account the influence of the adjustment fac-

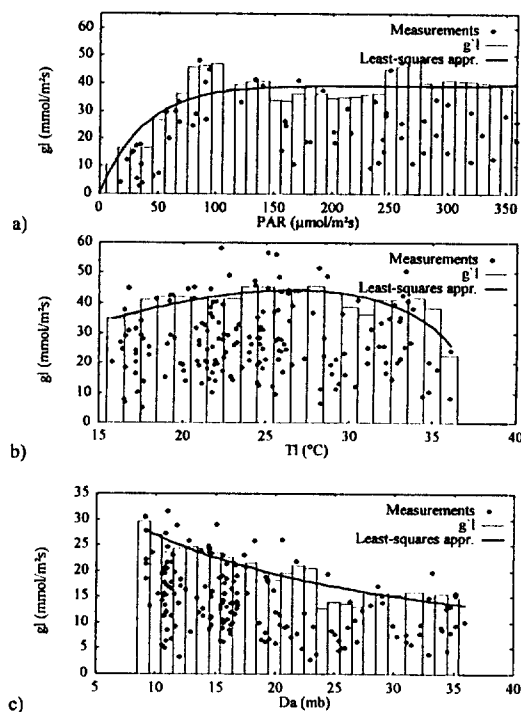


Fig. 2(a-c). Dependencies of g_{lup} on incoming PAR, needle temperature and water vapour deficit in air. The functions(solid curves) were fitted using a least-squares procedure for 90 percentage points(boxes)(g'_{lup}) of cumulative probability distribution function $F(g_{lup})$ calculated for each interval of PAR, T_{lup} , D_a .

tors $f_1(PAR) \cdot f_2(T_l) \cdot f_3(D_a)$ (Fig. 2(a-c)).

An initial analysis of environmental dependencies of needle stomatal conductance shows that the regulation of water loss from spruce is strongly controlled by the guard cells of the needle stomata. The g_{lup} increases very rapidly with PAR when it is less than $120 \mu\text{mol m}^{-2} \text{s}^{-1}$ and virtually independent on PAR when it is greater than $120-150 \mu\text{mol m}^{-2} \text{s}^{-1}$. An increase of temperature and a decrease of water vapour deficit tends to increase g_{lup} . When the temperature exceeds some critical temperature value (which corresponds to the optimal temperature for stomatal functioning $T_{lup, opt.} = 26.7^\circ\text{C}$) g_{lup} rapidly falls. The constants of the regression lines and their standard errors are given in Table 3.

Table 3. The values of the parameters of needle stomatal conductance(g_{st}) functions(Eqs. 27-30) and their standard variability are determined at the spruce forest in Solling.

Parameters	Symbols	Values of parameters and standard errors
Empirical parameter determining the slope of the light response curve	β_{st}	$0.0267 \pm 0.0056 \mu \text{mol}^{-1} \text{m}^2 \text{s}$
Lower temperature limit for stomatal functioning	$T_{l \text{ min}}$	$0.00 \pm 0.00 \text{ }^\circ\text{C}$
Optimal temperature for stomatal functioning	$T_{l \text{ opt}}$	$26.71 \pm 0.76 \text{ }^\circ\text{C}$
Upper temperature limit for stomatal functioning	$T_{l \text{ max}}$	$37.44 \pm 0.60 \text{ }^\circ\text{C}$
Empirical parameter determining the slope of $f_s(D_n)$	α	$0.0635 \pm 0.0113 \text{ mbar}^{-1}$

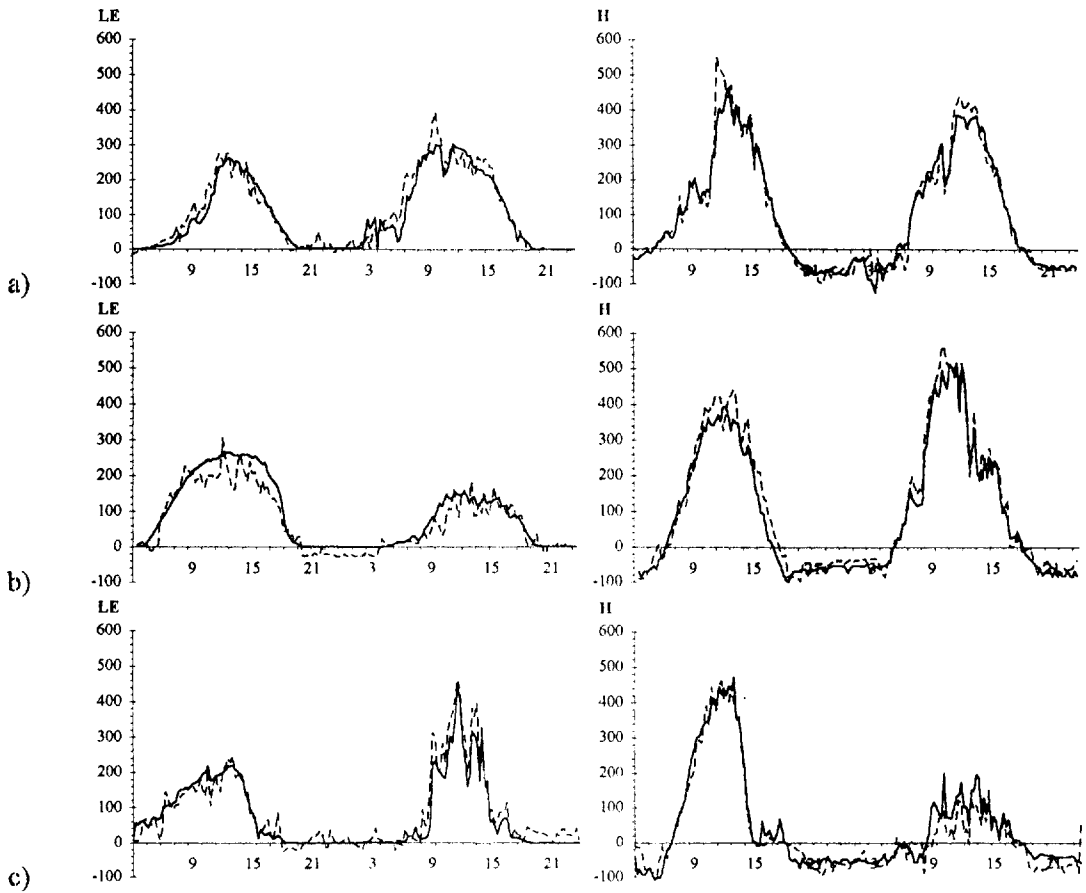


Fig. 3(a-c). Comparisons between simulated (solid curves) and measured(dotted curves) LE and H in spruce forest for three 2-day validation periods(27-28 June, 28-29 July and 23-24 August 1994, respectively).

2. Comparison of modelled and measured latent and sensible heat fluxes.

Comparisons between simulated and measured LE and H of selected periods show a good agreement for a variety of weather and soil water

conditions(Fig. 3(a-c)). The highest discrepancy between predicted and observed LE and H was found for periods of rainy and wet weather conditions(during the early hours of the morning on 28 June after a small rain(1.2mm/day) during the

night and on 24 August with short-lived showers (12.2mm/day) and very high air relative humidity). For periods with dry and cloudless weather (on 27-28 June 1994 the maximum solar radiation was 870.4W/m^2 and maximal temperature reached 25.4°C , and on 28-29 July 1994 the maximum solar radiation was 818.0W/m^2 and maximal temperature reached 29.5°C) under non-limited and limited soil water conditions ($\psi_s=92-102$ mbar(27-28 June 1994), $\psi_s=422-502$ mbar(28-29 July 1994)) the differences between predicted and observed LE and H were minimal. In general for selected periods the SLODSVAT explained 90% of the variation of LE ($r^2=0.903$) and 96% of the variation of H ($r^2=0.958$) (Fig. 4(a-b)). The scatter between modelled and observed fluxes can have several reasons. Obviously, the simplifications made in the model, e.g. simplified consideration of canopy architecture, ignoring the vertical heterogeneity in responses of needle stomatal conductance to changes of environmental conditions, simplified parametrisation of the complex hydraulic structure of spruce trees can insignificantly reduce the accuracy of model predictions. Moreover, it is necessary to take into account the possible errors caused by inaccuracies of field observations. Usually, using the Bowen ratio method under relatively contrast weather conditions can result in errors which are not exceed 5-10%.

Analysis of the diurnal trends of modelled and observed LE and H shows that during the periods of sunny and warm weather without rains(27-28 June, 28-29 July, 23 August) H was

generally higher than LE . The Bowen ratios($Bo = H/LE$) tended to obtain a broad plateau of about 1.2-1.6 between 08:00-16:00 h. Lower and negative Bowen ratios were generally obtained around sunrise and sunset. For period of rainy weather Bo varied between 0.3-0.8.

The relatively high Bowen ratios for periods of sunny warm weather can be caused by a complex of factors, namely, tree-water stress during a dry afternoon, high D_a values and insufficient for maximal stomatal conductivity T_a .

3. Sensitivity of transpiration rate to changes in model parameters

The results show that the modelled transpiration rate(E) is most sensitive to the canopy stomatal conductance(g_{up}) and to the difference of water vapour pressure between saturated air in the substomatal cavities and in the canopy air space(D)(the variability of g_{up} and D provides 63.6% and 46.2% of the variability of E , respectively) and to a lesser degree to the boundary aerodynamic resistance between the foliage surface and the surrounding air space within the canopy layer(r_b)(about 1.0%, only). However, it is necessary to take into account that r_b is a key parameter determining the gradient of temperature between the foliage surface and the surrounding air. In general, r_b is proportional to wind speed in the canopy(Eq.13). Therefore, a low wind speed under warm and dry weather conditions can lead to overheating of the canopy surface and, consequently, to limiting the stomatal

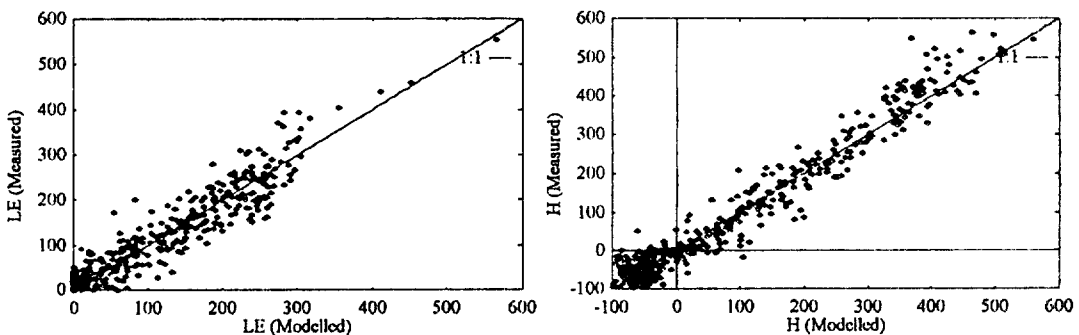


Fig. 4(a-b). Scatter view between simulated and measured LE ($r^2=0.903$, $n=538$ cases) and H ($r^2=0.958$, $n=538$ cases).

conductivity and transpiration rate.

The modelled g_{up} was most sensitive to the variation of incoming PAR(79% variability). The significance of T_a , D_a and ψ_l for g_{up} during selected periods was small, namely, the variability of T_a , D_a and ψ_l results in 9.6%, 7.0% and 19.0% of the diurnal variability g_{up} , respectively. Additionally, it should be once more emphasised that the influence of T_a and D_a on g_{up} is very complicated due to available feedback effects and interdependencies between incoming PAR, T_a and D_a . Variation of one of these parameters leads simultaneously to a change of other parameters and in some cases can result in opposite effects in stomatal responses.

CONCLUSION

Comparison of modelled results with the results of field microclimatic observations in a spruce forest in Solling hills for three two-day periods shows that the SLODSVAT describes and simulates the diurnal variability and long term variations of sensible heat and water vapour fluxes adequately the natural processes under different meteorological and hydrological conditions and phenological states of a spruce forest. The SLODSVAT explained 90% of variation of LE ($r^2=0.903$) and 96% of the variation of H ($r^2=0.958$). The results prove that it is possible to estimate and predict evapotranspiration and transpiration rates for forest ecosystems in the patch scale for one vegetation period if appropriate input parameters for the soil and canopy structures are available.

Analysis of environmental dependencies of needle stomatal conductance shows that the regulation of water loss from spruce is strongly controlled by the guard cells of needle stomata. For selected periods the transpiration rate(E) was most sensitive to the variation of canopy stomatal conductance(g_{up}) and to the gradient of water vapour pressure between saturated air in the substomatal cavities and water vapour pressure in the canopy air space(D)(the variability of g_{up} and D provides 63.6% and 46.2% of the variability of E , respectively). The modelled g_{up}

was most sensitive to the variations of incoming PAR(79% variability of g_{up}).

This article presents the results of comparisons of modelled and measured LE and H for three short periods during June - August 1994 only. It should be emphasised that the correspondence between measured and modelled LE and H for other periods was also comparatively good. The results of model tests already made for radiation transfer, canopy water uptake through the roots, soil water dynamic, CO_2 assimilation are not included in this paper. We hope that they will be presented in one of the following essay.

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