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Annales Geophysicae

Quantifying the coupling degree between land surface and the atmospheric boundary layer with the coupled vegetation-atmosphere model HIRVAC

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Abstract. In the present study, the ability of different indices to quantify the coupling degree between a vegetated surface and the atmospheric boundary layer is tested. For this purpose, a one-and-a-half dimensional atmospheric boundary layer model, including a high resolved vegetation canopy, was applied (HIRVAC) and indices, such as the decoupling factor Ω, as well as other measures derived from model output were used. The aim of the study was to show that the quite complex coupling and feedback mechanisms can be described with these relatively simple measures. Model results illustrate that the vegetation and the atmosphere are well coupled (expressed by a lower Ω) under conditions of a tall and dense canopy, as well as under strong dynamic forcing. This better aerodynamic coupling leads to an increase in evapotranspiration, as well as an increase in the evaporative fraction. This fact was also shown by the second coupling measure: the relative changes in daily model evapotranspiration. This measure was inspired by the assumption that these changes are primarily dependent on the coupling degree between the surface and the atmosphere, if the other boundary conditions in the model are fixed. A third sensitivity measure was used according to Jacobs and de Bruin (1992). It shows that the sensitivity of evaporative fraction to stomata resistance is much higher with a better aerodynamic coupling. The results of the factor Ω are in a good agreement with the findings of Jacobs and de Bruin: they stress that it is a valuable strategy to group vegetation into two simple categories (smooth and rough) for the understanding of vegetation-atmosphere coupling.

Key words. Atmospheric composition and structure (biosphere-atmosphere interactions) – Hydrology (evapotranspiration; hydroclimatology)

Abbreviations

HIRVAC, HIgh Resolution Vegetation Atmosphere Coupler;
AST, Anchor Station Tharandt;
ABL, Atmospheric Boundary Layer;
TKE, Turbulent Kinetic Energy;
HUB, Humboldt University of Berlin;
PSN6, Photosynthesis model (University of Bayreuth);
ET, Evapotranspiration;
VPD, Vapour Pressure Deficit;
LAD, Leaf Area Density;
LAI, Leaf Area Index.

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1 Introduction

Many authors have stated that a more physical description of vertical and horizontal feedback mechanisms between the vegetated surface and the atmosphere in climate models of different scales is very important for the quality of the simulated output (e.g. in the micro-scale: Jacobs and de Bruin, 1992; Kroon and de Bruin, 1993; Su et al., 1996; Daudet et al., 1999; in the meso-scale: Pinty et al., 1992; and in the macro-scale: Lofgren, 1995; Claussen, 1997; Claussen et al., 1998; Beniston and Innes, 1998; Varejão-Silva et al., 1998). It was also demonstrated that the primarily implemented "bigleaf" approaches (Pinty et al., 1992; Sellers et al., 1996) are able to roughly describe the interactions between the land surface and the atmosphere. Remaining uncertainties are at least partly due to inadequate parameterisation of sub-scale characteristics, such as complex topography and land use (e.g. Mölders and Raabe, 1996), as well as the rapid change of the micro-scale turbulent regime by the highly variable sources and sinks of vegetation itself. This leads, for instance, to inaccuracies in the parameterisation of surface and aerodynamic resistances, as well as gradients of physiological quantities and heat source distribution (Daudet et al., 1999) which drive the interaction between the vegetation and the atmospheric boundary layer. In nature, it is impossible to carry out "twin" experiments to prove the effect of coupling between the land surface and the atmosphere. Furthermore, the use of "historical data" leads to validation problems because these data implicitly include feedbacks which cannot be separated. Therefore, the use of a model is a means of

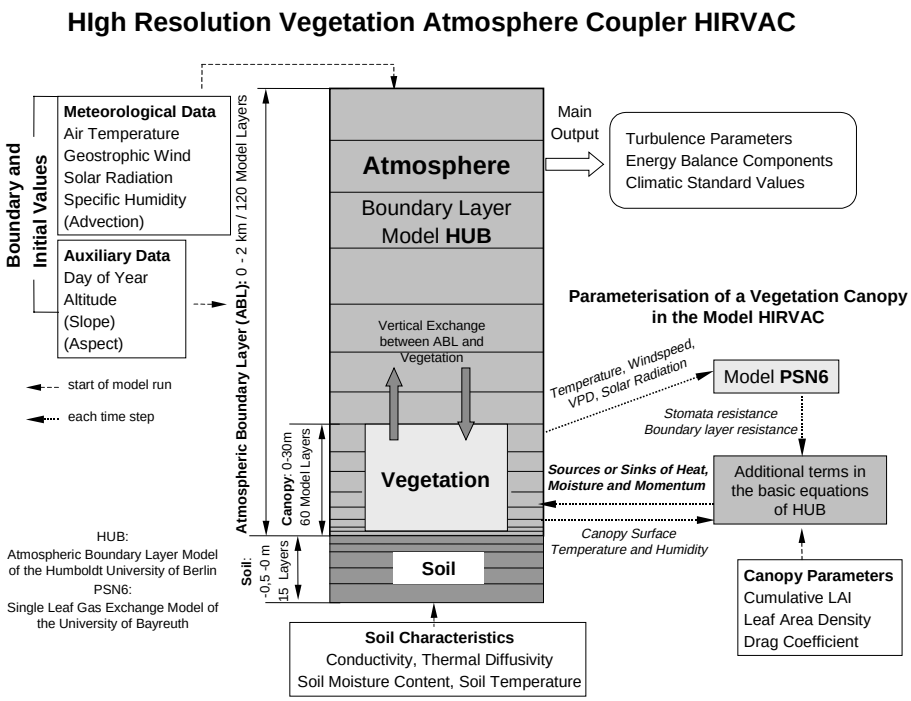

Fig. 1. Scheme of the model HIRVAC.

extracting and investigating "single" coupling processes. In this study, results of numerical experiments, with the coupled vegetation-atmosphere model HIRVAC, are used to investigate the above mentioned coupling mechanisms.

2 Method

2.1 Model HIRVAC

Figure 1 shows the current scheme of the HIRVAC model. HIRVAC (HIgh Resolution Vegetation Atmosphere Coupler) is a one-and-a-half-dimensional atmospheric boundary layer model (HUB) which includes a vertical high resolved vegetation canopy (based on the boundary layer model after Mix et al. (1994), modified by Ziemann (1998)). The horizontal advection can be given in parameterised form. The model has 120 layers between the lower (surface) and the upper (boundary layer height) model border (layer distance increases with a geometric progression), where 60 layers are in the first 30 meters above the ground. This is a typical height for tall canopies, such as forests. The vegetation is included in the model structure of HIRVAC by additional source and sink terms in the basic equations of motion (Eqs. 1 and 2), temperature (Eq. 3), moisture (Eq. 4) and turbulent kinetic energy (TKE) (Eq. 5). In the model, a one-and-a-half turbulence closure is applied by using the TKE-equation (5), the mixing length formulation by Lajhtman and Zilitinkevič, as well as Kolomogorov's expression of the turbulent-transfer coefficient (see also Mix et al., 1994; Ziemann, 1998).

$$\frac{\partial v_x}{\partial t} = f(v_y - v_{gy}) + \frac{\partial}{\partial z} K \frac{\partial v_x}{\partial z} - j\left\{ n_w c_d LAD v_x \sqrt{\left(v_x^2 + v_y^2\right)} \right\} \quad (1)$$

$$\frac{\partial v_y}{\partial t} = -f(v_x - v_{gx}) + \frac{\partial}{\partial z} K \frac{\partial v_y}{\partial z} - j\left\{ n_w c_d LAD v_y \sqrt{\left(v_x^2 + v_y^2\right)} \right\} \quad (2)$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} K_T \frac{\partial \theta}{\partial z} + (1 - j n_w) \frac{1}{\rho c_p} \frac{\partial B_{lw}}{\partial z} + j\left\{ \frac{LAD}{r_b} (T_W - T) \right\} \quad (3)$$

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial z} K_q \frac{\partial q}{\partial z} + j\left(\frac{LAD}{r_b + r_s} (q_W - q) \right) \quad (4)$$

$$\frac{\partial b}{\partial t} = K\left[\left(\frac{\partial v_x}{\partial z}\right)^2 + \left(\frac{\partial v_y}{\partial z}\right)^2 \right] + \frac{\partial}{\partial z} K_b \frac{\partial b}{\partial z} - \frac{g}{\theta} K_T \frac{\partial \theta}{\partial z} - 0.608 g K_q \frac{\partial q}{\partial z} - \alpha_\varepsilon \frac{b^2}{K} + j\left\{ n_w LAD c_d \sqrt{\left(v_x^2 + v_y^2\right)^3} \right\} \quad (5)$$

where z is the vertical coordinate; v_x, v_y are the components of horizontal wind speed; v_{gx}, v_{gy} are the components of geostrophic wind speed; θ is the potential temperature; b is the turbulent kinetic energy; α_ε is the coefficient of energy dissipation; K, K_T, K_q, K_b are the turbulent-transfer coefficients for momentum, heat, moisture and turbulence kinetic energy; f is the coriolis parameter, B_{lw} is the long-wave atmospheric radiation; g is the gravity acceleration; $n_w = 0 \ldots 1$ represents crown cover; $c_d = 0.1 \ldots 0.3$ represents drag coefficient; LAD is the leaf area density; r_b,

r_s are the boundary layer and stomatal resistance; T_W, T are the temperature of the vegetation surface and the ambient air; q_w is the specific saturation humidity at T_W; q is the specific humidity of the ambient air; $j = 1$ inside and $j = 0$ above the canopy. To calculate the lower boundary conditions of temperature and moisture, a multi-layer soil model for heat transfer and a one-layer model of moisture content after Groß (1993) are used. The upper boundary conditions of temperature and moisture are boundary conditions of the third order, i.e. variable vertical profiles of temperature and moisture at the top of the boundary layer exist and the values of turbulent-transfer coefficients are not exactly zero. The boundary values are permanently adapted to an "imaginary" sink outside the top of HIRVAC and thus, a small entrainment is realized. A more detailed explanation of boundary and initial conditions is documented in the literature (Mix et al., 1994; Ziemann, 1998).

The boundary layer and stomatal resistances are calculated by a mechanistic photosynthesis model (PSN6 – Falge et al., 1996) at each time step and for each model layer in the canopy space with the meteorological data input from the boundary layer model. This physiologically-based description of the exchange between a highly resolved vegetation canopy and the boundary layer is an adequate basis to simulate "realistic" coupling mechanisms between a vegetated surface and the atmospheric environment.

In this study, the advection is not considered. This leads to a limitation but also to a simplification of coupling mechanisms. On the one hand, only the vertical exchange between a quasi homogeneous land surface and the atmosphere can be investigated. On the other hand, the coupling mechanisms, due to vertical exchange, can be separated easier and studied without the "disturbances" due to the influence of advection (e.g. edge effects, see Kroon and de Bruin, 1993).

2.2 Coupling indices

2.2.1 Omega-factor

To quantify the coupling between a vegetation canopy and the atmospheric boundary layer, different coupling measures were tested with the model HIRVAC. First, the decoupling coefficient, Ω, (McNaughton and Jarvis, 1983) was investigated. This coefficient was used by many authors (e.g. Martin et al., 1989; Monteith and Unsworth, 1990; Jacobs and de Bruin, 1992; Daudet et al., 1999) and describes the degree of aerodynamic coupling between the vegetation and the atmospheric boundary layer, as well as the degree of transpiration control by the vegetation. After Monteith and Unsworth (1990), the factor Ω is given by

$$\Omega = \frac{s + \gamma}{s + \gamma(1 + r_s/r_a)} \tag{6}$$

with s as the slope of the saturation curve; γ as the psychrometric constant; r_a as the aerodynamic resistance; r_s as the canopy resistance.

If the turbulent energy fluxes are known (e.g. from the output of a boundary layer model), the resistances can be calculated with "bulk" approaches for heat and moisture transfer between the "active surface" and a reference level above the canopy. In the active surface, the energy exchange, due to the divergence in radiation fluxes, reaches a maximum. The height of this surface above zero-plane displacement, d, corresponds to the roughness lengths of the underlying surface (see, e.g. Brutsaert, 1982; Monteith and Unsworth, 1990). For the model studies in this paper, the height of the active surface was adjusted to the height of maximum leaf area density (20 m in the forest stand) and the roughness length of grass at a 15 cm height (2 cm, see also Brutsaert, 1982). The above mentioned reference level should be situated in the dynamic sublayer above the canopy. The height of this layer depends on the roughness length of the canopy and the thermal stratification of the boundary layer. In the case of non-neutral stratification, the dynamic sublayer ranges over a magnitude of 1 to 10 meters. To avoid the influence of the canopy roughness layer (1.5 to 3.5 times of roughness length, see Brutsaert, 1982), a height of 2 m was used for the reference level over grass. The reference level for the model experiments with the forest stand corresponds to the highest measuring level of the Anchor Station Tharandt – AST (40 m), the forest site used for validation.

With the assumption that the heat transport only depends on aerodynamic resistance and the moisture transport depends on canopy and aerodynamic resistance, one arrives at the following formulation:

$$r_a = \rho c_p (T_0 - T)/H \tag{7}$$

$$r_s = \rho L (q_s(T_0) - q)/L.E - r_a \tag{8}$$

with H, $L.E$ represent sensible heat flux, latent heat flux between the active surface inside and the above mentioned reference layer above the canopy; ρ is the air density; c_p, L are the specific heat capacity of dry air, heat of vaporisation; T_0, $q_s(T_0)$ are the temperature and specific saturation humidity of the active surface (2 cm height for grass and 20 m height for the spruce stand); T, q are the temperature and specific humidity of the corresponding reference layer above the canopy (2 m height for grass and 40 m height for the spruce stand).

Extreme cases for r_a yields two contrasting cases of aerodynamic coupling:

$\lim_{r_a \to 0} \Omega = 0$: The vegetation and the atmosphere are fully aerodynamically coupled. The transpiration is controlled by the stomatal resistance and the VPD (vapour pressure deficit) between canopy surface and atmosphere (Martin, 1989). This "boundary layer feedback" has a large influence on the sensitivity of transpiration (Jacobs and de Bruin, 1992).

$\lim_{r_a \to \infty} \Omega = 1$: The vegetation and the atmosphere are fully aerodynamically decoupled. The transpiration is controlled by the available energy (Martin, 1989). This is the case of a ideal "surface layer feedback" (Jacobs and de Bruin, 1992).

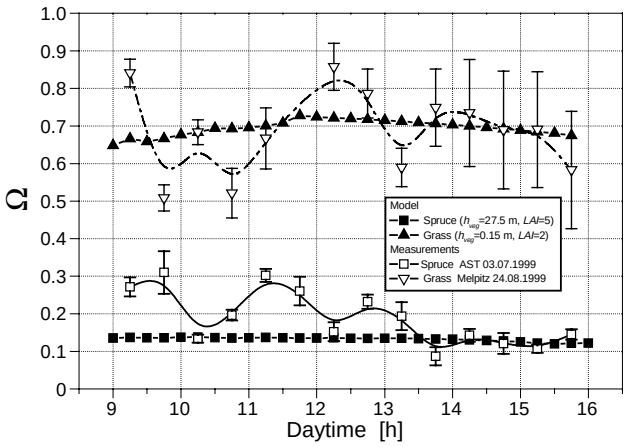

Fig. 2. Dependence of the decoupling coefficient Ω on the type and height of vegetation; comparison of results from HIRVAC simulation with measurements from 3 July (spruce) and 24 August (grass) under clear sky conditions (error bars – standard deviation of 10-min-measurements).

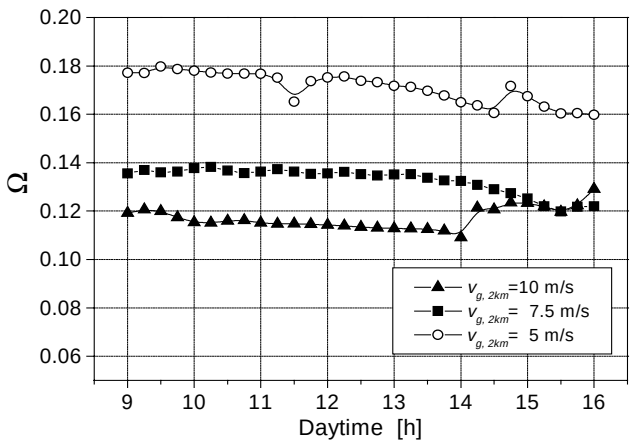

Fig. 3. Dependence of the decoupling coefficient Ω on geostrophic wind speed; simulation with the model HIRVAC for 3 July and clear sky ($h_{\text{veg}} = 27.5$ m, $n_w = 0.8$, $LAI = 5$).

2.2.2 Time changes of surface fluxes

If the boundary conditions in the model HIRVAC are fixed, the change in evapotranspiration (ET) between different simulated model days of the same model run depends on the coupling degree between the vegetation, as source, and the atmosphere, as sink of moisture. Thus, the ratio of daily sums of ET is a measure of coupling and feedback between the canopy and the atmospheric boundary layer, as well as a measure of a drier or a wetter atmosphere.

2.2.3 Sensitivity measures after Jacobs and de Bruin

In Jacobs and de Bruin (1992), different measures derived from the Penman-Monteith-equation were tested to investigate the interaction between surface and boundary layer feedback and the control of transpiration by a vegetated surface. To show the influence of changed vegetation parameters and atmospheric conditions on the above mentioned interactions, the sensitivity of the relation between evapotranspiration and net radiation to canopy resistance, S_{rs} was used. This term is expressed based on Jacobs and de Bruin (1992) as follows:

$$S_{rs} = \frac{\partial\,(L.E/R_N)}{\partial r_s} = \frac{-\gamma' L.E/R_N}{[(s+\gamma')r_a + \gamma' r_s]} \tag{9}$$

where R_N is the net radiation at the surface and $\gamma' = c_p/L$.

3 Results and discussion

The model results were calculated for the radiation input of a clear summer day (solstice), soil parameters of sandy loam, and 20°C in a soil depth of 50 cm. A boundary condition of the third order (variable gradients) for temperature and moisture in a height of 2 km was used. To describe the vegetation structure of a forest, the vertical profile of leaf area density (LAD, see Eqs. 1 to 5) was fitted to a typical old spruce stand, such as those located at the Anchor Station Tharandt (AST), with a crown cover of 80 percent, a Leaf Area Index (LAI) of 5, albedo of 7 percent, and a vegetation height (h_{veg}) of 27.5 m. The grass stand was parameterised by a constant LAD profile with a LAI of 2, albedo of 20 percent, and a vegetation height of 0.15 m. The model was run for 6 simulation days. The first simulation day was used to obtain a dynamic initialisation for the following simulation period (initial conditions adapted to the boundary conditions). The results of the second simulation day were used for the calculation of the Ω-factor (Figs. 2 and 3) and the sensitivity measure after Jacobs and de Bruin (Fig. 6). The results of the sixth simulation day were used additionally for the calculation of the time changes of surface fluxes (Figs. 4 and 5). The computational time for a 6 day simulation was about 1 minute on a Pentium II / 266 MHz computer.

Figure 2 illustrates the dependence of the decoupling coefficient Ω on the type and height of vegetation. The best coupling with the atmosphere (low values for Ω) is given for tall and rough vegetation, such as a a forest canopy (solid and open squares), where low and smooth canopies, such as grass, show a stronger aerodynamic decoupling from the atmosphere (solid and open triangles). In the case of the spruce stand, the aerodynamic resistance is low and the transpiration is primarily controlled by stomatal resistance (see also Martin, 1989). The aerodynamic resistance for the smooth grass surface is relatively high and the stomatal resistance is low. A feedback between the vegetation and the atmosphere occurs at the active surface (surface layer coupling, see also Jacobs and de Bruin, 1992). The modelled values (solid symbols) were compared for a clear summer day, with results of the Ω-factor derived from measured data over spruce (AST, open squares) and over pasture (Melpitz, open triangles), respectively. The measured and modelled data show a reasonable agreement in the averaged daily course in the case of the grass stand, but only a partial agreement in the daily course

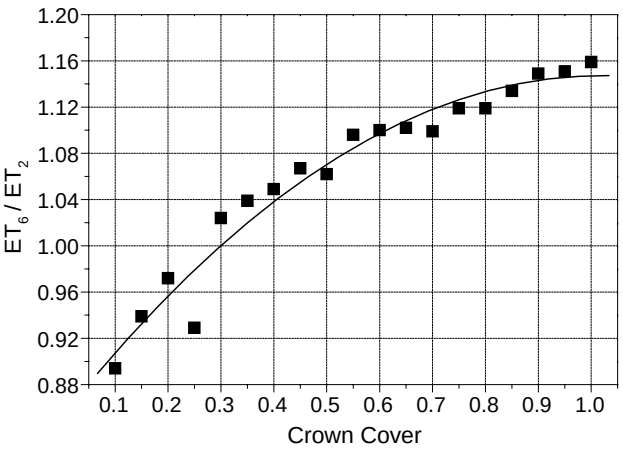

Fig. 4. Relation in daily sum of evapotranspiration between model days 6 and 2; dependence on crown cover; simulation with the model HIRVAC for 21 June, clear sky and a spruce stand ($h_{\text{veg}} = 27.5$ m, $LAI = 5$).

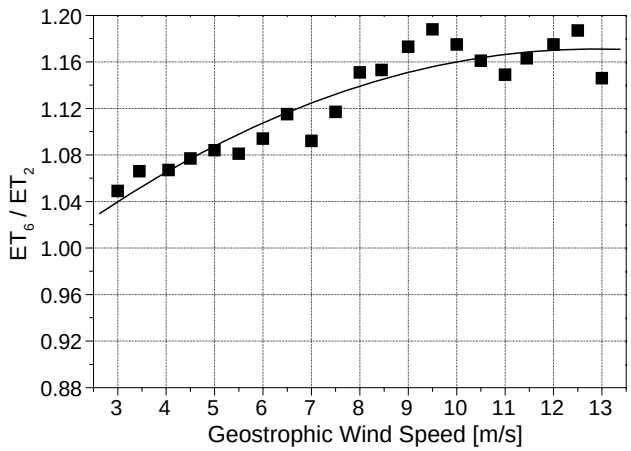

Fig. 5. Relation in daily sum of evapotranspiration between model days 6 and 2; dependence on geostrophic wind speed; simulation with the model HIRVAC for 21 June, clear sky and a spruce stand ($h_{\text{veg}} = 27.5$ m, $LAI = 5$).

of the Ω-factor in the case of the spruce canopy. On the one hand, these differences could be due to an inaccurate determination of the initial conditions in comparison to the measurements, or to the inaccuracies of the measurements themselves (see error bars in Fig. 2). On the other hand, these differences can be due to an insufficient description of the turbulence regime in the HIRVAC model.

Figure 3 illustrates the dependence of the decoupling coefficient Ω on the geostrophic wind speed, as an important atmospheric boundary condition of the model HIRVAC. The results show that an increasing dynamic forcing leads to an increasing aerodynamic coupling of one and the same canopy (a spruce forest, in this case) with the atmosphere, as well as a qualitative change in the daily course of Ω.

To show the influence of vegetation atmosphere coupling on time changes of surface fluxes, the ratio in modelled daily evapotranspiration was calculated, dependent on vegetation and atmospheric parameters. Thus, the crown cover (n_w) of a spruce stand and the geostrophic wind speed at the top of the boundary layer ($v_{g,2\,\text{km}}$) were varied from 0.1 to 1.0 (standard value: 0.8 = 80 percent, see above) and from 3 to 13 m/s (standard value: 7.5 m/s), respectively. For each six day simulation, only one parameter was changed and the other boundary conditions were fixed to the standard values.

Figures 4 and 5 demonstrate the dependence of the ratio in modelled daily evapotranspiration between the sixth and second simulation days ($ET_6/ET_2 = ET(\text{6th day})/ET(\text{2nd day})$) on changes in these parameters. The results generally demonstrate that the denser the canopy is and the stronger the dynamic force is, the stronger the evapotranspiration increase will be in a model run. The model results were fitted by the polynomial functions

$$ET_6/ET_2 = 0.85 + 0.58 n_w - 0.28 n_w^2 \quad (10)$$

$$ET_6/ET_2 = 0.95 + 0.035 v_{g,2\,\text{km}} - 0.001 v_{g,2\,\text{km}}^2 \quad (11)$$

with a relatively high statistical check ($r^2 = 0.95$ for Eq. (10) and $r^2 = 0.87$ for Eq. (11)).

The comparison between Fig. 3 and Fig. 5 implies that the better the aerodynamic coupling (lower values of Ω) is, the stronger the evapotranspiration increase is in a model run.

Finally, Fig. 6 displays the sensitivity of the ratio $L.E/R_N$ to a change in the canopy resistance r_s. The results confirm the remarks made regarding the results of Figs. 1 and 2. Under a well developed turbulent regime (second half of the day), the above mentioned ratio is less sensitive to the canopy resistance for the smooth grass canopy, than in the case of the spruce stand. The evapotranspiration over grass primarily depends on the net radiation, while the transpiration over the forest canopy is primarily controlled by the canopy. In the second case, the vegetation is aerodynamically well coupled and feedbacks between the surface and the atmosphere occur over the whole atmospheric boundary layer (see Jacobs and de Bruin, 1992).

4 Summary and conclusions

The results clearly show that the vegetation-boundary-layer model HIRVAC is able to describe, qualitatively, coupling mechanisms between a vegetated surface and the atmospheric boundary layer, with the presented coupling indices. These coupling indices also allow a quantification of the coupling degree. These model characteristics can be applied to separate single coupling mechanisms (e.g. surface and boundary layer controlled), as well as to describe the influence of single parameters (of the land surface or of the atmosphere) to the coupling mechanisms which is impossible in the field. Another application is the simulation of potential changes in land use and its influence on the vegetation-atmosphere coupling.

As a first measure the well established decoupling factor Ω was calculated with the HIRVAC output for a clear summer day and the results were compared with measured data for a

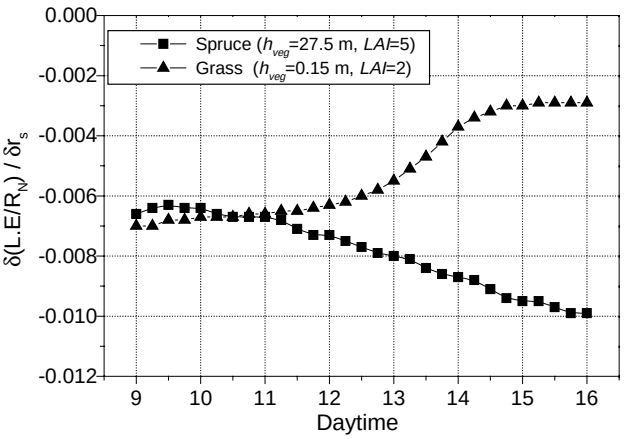

Fig. 6. Sensitivity of the evaporative fraction to canopy resistance dependent on the type and height of vegetation; simulation with the model HIRVAC for 3 July and clear sky.

spruce stand and a grass canopy. The values of Ω correspond to the results from other authors (Jacobs and de Bruin, 1992; Kelliher et al., 1990; Pinty et al., 1992). The daily mean of the measured and modelled data for the grass stand show adequate agreement. The differences in daily course could be due to inexact determination of the soil moisture, which leads to differences in the calculated canopy resistance in the model and the experiment. In the case of the spruce stand, there are differences between the measured and modelled Ω values, especially in the first half of the day. Possible reasons for this are the insufficient height of the reference level above the spruce stand in the measurements and the lack of a description of large eddies in the model HIRVAC.

Results for the evaporation ratio between the sixth and second simulation days, as the second coupling measure demonstrates, that this ratio increases with the crown cover and the geostrophic wind speed. Other model results simultaneously show that the decoupling coefficient Ω decreases when the geostrophic wind speed increases. This allows, on the one hand, the conclusion that if the other boundary conditions are fixed, the evapotranspiration only increases if there is a better aerodynamic coupling with the atmosphere, and on the other hand, an increasing crown cover leads to a better aerodynamic coupling between the canopy and the atmosphere.

The investigated sensitivity of the evaporative fraction to canopy resistance clearly shows the interaction between the dominating coupling mechanism and the transpiration controlled by the vegetation. For the grass canopy, the decoupling coefficient Ω is high and the evapotranspiration primarily depends on the net radiation (surface layer feedback). The vegetation has only slight control of transpiration and the above mentioned sensitivity is relatively low. In the case of the spruce stand, the value of Ω is low and the transpiration primarily depends on the atmospheric conditions (VPD and wind speed) and the canopy resistance (boundary layer feedback). The vegetation can better control the transpiration and the above mentioned sensitivity is relatively high.

The model results illustrate the importance of the coupling mechanisms to the evapotranspiration of a vegetated surface. Further studies will integrate the dependence of the coupling measures on different vegetation parameters and atmospheric conditions into few practicable "parameter functions" which will consider the effect of coupling in well established approaches (e.g. Penman-Monteith). For this reason, a more detailed validation of the model experiments with measured data under different atmospheric conditions, as well as the calculation of coupling measures from generally accessible landscape indices (e.g. LAI from satellite measurements, vegetation height and vegetation density from forestry offices) is necessary.

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