JP5.5 MODELING OF THE FOREST GAPS-FOREST INTERACTION

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1. INTRODUCTION

Gaps in a forest are common elements of landscape. Forest edges created by natural processes (wind throw, fire) or by logging affect forest structure and function. In this paper, we consider only those effects that are important in relation to surface-atmosphere exchange study. There are few detailed field experiments aimed at the study of turbulence structure and exchange processes of different substances in proximity of the forest edge interface (Kruijt, 1994; Irvine et al., 1997; Morse, 2002). Such processes considerably impact the interaction between surface and the atmosphere and their understanding is essential in many practical applications. In contrast with the scale of experiments required to examine the in-depth spatial variation of physical processes, for instance, downwind of a sharp forest-clearcut discontinuity, modeling provides a cheap and useful way to investigate spatially dependent complex processes. Nowadays, large-eddy simulation (LES) and higher-order closure (HOC) models are still computationally intensive to explore the open place-forest patch area. *K-l* models existed (*K* is the turbulent diffusivity and *l* - mixing length) are simple but they only allow a gradual change from an upwind mixing length to a downwind equilibrium value. Such kind of models allow the mixing length to drop below the equilibrium value as a result of vertical advection and that is not sufficient to simulate the drop of turbulent diffusivity observed close to the edge (Kruijt, 1994). As compromise, results from a two-equation model which does not require a predefined mixing length and which includes a new parameterization for drag term are presented. These results reflect recent achievements in modeling of the forest gaps-forest interaction.

2. MODEL

The numerical atmospheric boundary-layer (ABL) SCADIS model based on E-ω scheme (where *E* is turbulent kinetic energy and ω is specific dissipation of *E*) has been used as the basis for the present study. Model equations and details about numerical schemes and boundary conditions can found in Sogachev et al. (2002, 2005a, 2005b). Only some details about canopy parameterization and footprint modeling approach will be given here.

2.1 *Accounting for vegetation*

The two-dimensional governing equations to be solved are those for mass and momentum conservation (Navier-Stokes) with a conventional parameterization for the momentum sink of canopy elements S_i following the method described by Raupach and Shaw (1982)

$$S_i = -c_d\, A(z) U_i U, \tag{1}$$

where the subscript *i* distinguishes the direction for components of velocity U_i, *U* is the mean flow velocity, *A(z)* is the projected leaf area per unit volume or leaf area density (LAD), and c_d is the effective drag coefficient. To consider the effect of vegetation on *E* and ω, we use the parameterization suggested by Sogachev and Panferov (2006). According to the latter, no additional terms related to plant drag appear in equations for *E* and ω, but only coefficient C_2 determining the rate of turbulence decay within a vegetation canopy is updated as

$$C_2^* = C_2 - \frac{(C_2 - C_1) S_d}{E\omega}, \tag{2}$$

where C_1 is the coefficient by shear production term in the ω-equation, and S_d denotes the enhanced dissipation due to plant drag. The latter is expressed as (Sanz, 2003)

$$S_d = \beta_d\, c_d\, A(z) U E, \tag{3}$$

The coefficient β_d shows the magnitude of turbulent kinetic energy losses on interactions with obstacles.

The term describing sources/sinks inside the canopy layer (S_c) depends on both the leaf aerodynamic resistance (r_a) and the stomatal resistance (r_s) and is expressed as

$$S_c = \frac{\delta A(z)(C_{in} - C)}{r_a(z) + r_s(z)} \tag{4}$$

The parameter δ is the ratio between the total and the projected leaf surface area, with the product $\delta A(z)$ defining the total leaf surface involved in scalar exchange with the surrounding air. *C* is the atmospheric background scalar concentration, and C_{in} is the scalar

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concentration in the intercellular airspace. Complete expressions of C_{in} for CO2 and of both resistances could be found in Sogachev et al. (2002). In the case of neutral stratifications we used simplified expressions for these variables (Sogachev et al., 2005b).

2.2 *Footprint modeling*

Quantitatively, the relation between a source strength *Q* and the value of a signal *F* registered at the location ***r*** is described by "source weight function" or "footprint" *f* (Pasquall and Smith, 1983)

$$F(\mathbf{r}) = \int_{\Re} Q(\mathbf{r}+\mathbf{r}') f(\mathbf{r},\mathbf{r}') d\mathbf{r}' \tag{5}$$

where **r'** is the separation between the point of measurement and surface forcing, and $\Re$ is the integration domain. Several different approaches have been developed to estimate the footprint function (see Schmid (2002) for review). Recently, the footprint estimation based on the ABL model has been proposed by Sogachev et al. (2002) and analyzed in detail by Sogachev and Lloyd (2004).

The approach is based on the calculation of the individual contribution from each model cell to a vertical flux at a surrogate eddy-covariance tower. This is carried out by means of a comparative analysis of vertical flux fields formed by sources consecutively activated within the model domain. These fields are then normalized, yielding a contribution from each cell to the model surrogate tower flux. Since the forcing in each cell is a known quantity, the footprint function can be derived from the contribution of uniformly weighted source strengths. For further details, the reader is invited to see the description of this technique in Sogachev and Lloyd (2004).

3. RESULTS

3.1 *Model validation*

There exist a lot of experimental data about airflow characteristics inside the vegetation canopy. As a rule, such data have been derived from single-point measurements. In literature we can find many models (of different kinds including analytical ones) for the canopy flow that is mainly validated by using this data. Their applicability rather justifies for homogeneous conditions, but is questionable for heterogeneous ones. As it was mentioned in the Introduction there are few experiments explored turbulence characteristics in vicinity of forest edge. The lack of the experimental data limits seriously a development of high resolution flow models capable to take in to account the natural heterogeneity. Some examples of the model validation related to flow conditions around the forest edge will demonstrate below.

The results of a simulation for *E - l* model with a vegetation parameterization according to Wilson et al.

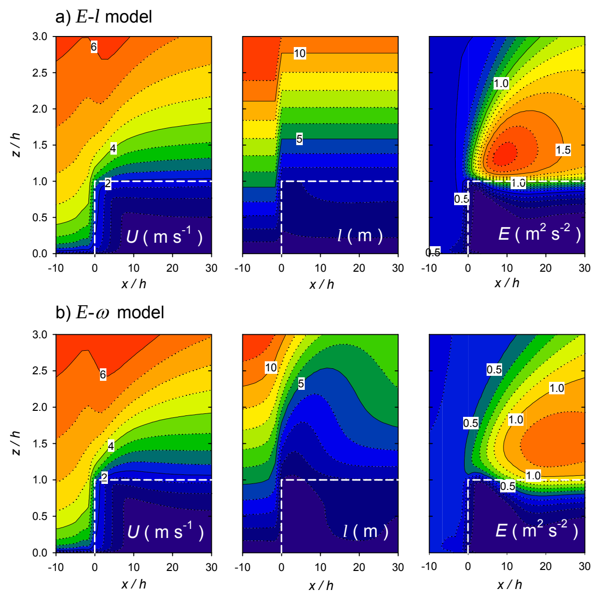

Figure 1: Two-dimensional fields of horizontal wind velocity (U), mixing length (l) and turbulent kinetic energy (E) near the leading edge of a forest derived by (a) E - l model with parameterization of Wilson et al (1998) and by E - ω model. The thick dashed line encloses the forest approximated by vertically uniform vegetation with a height of 15 m and LAI = 3. The horizontal distance is normalized by the tree height, x/h. Here and in figures below the airflow from the left to the right. (After Sogachev and Panferov, 2006).

(1998) and for our model with the inflow from an open area into a vegetation canopy are presented in Figure 1. The presented modelled fields of wind velocity do not show any considerable divergence between models. However, fields of other characteristics show some deviations, e.g. in the transition zone the *E - l* model fails to reconstruct the physical behaviour of the turbulence scale (Figure 1a). There are various approaches to correct *l* in this zone (Miller et al. 1991; Klaassen, 1992). Unfortunately, none of them is without any physical justification. The behaviour of the turbulence scale and the turbulence field in the case of our model corresponds qualitatively to that experimentally obtained by Krujit (1994) and by Morse et al. (2002). Comparison of model results with observations of Chen et al. (1995) for turbulent kinetic energy in wide gap downwind of the forest in Figure 2 shows that the model also deals well with the re-adjustment of the turbulence field on the leeside of a forest.

There are no general criteria guiding the validation of footprint models. Only a handful of validation experiments are available (see Foken and Leclerc, 2004). Therefore, the approach of footprint estimation based on SCADIS was mainly validated using comparison with other approaches. Figure 3 displays footprint predictions derived by different models for the same flow conditions over homogeneous vegetation.

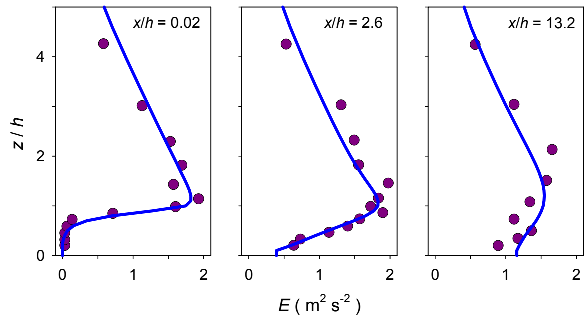

Figure 2 Comparison between vertical profiles of measured (symbols) and modelled (lines) turbulent kinetic energy, E downwind the model forest edge. The position at x/h = 0 corresponds to the beginning of the open place. (After Sogachev and Panferov, 2006).

The vegetation was presented by slash pine managed forest in Florida (Leclerc et al. 2003). The forest has a closed canopy with an average height of 13.5 m and LAI about 3. SCADIS footprints exhibit slightly different values from those of analytical and Lagrangian stochastic (LS) models. However, taking in account other benefits of SCADIS particularly with regards to computing cost and applicability to modelling complex flow over and within heterogeneous surfaces, SCADIS can be used cautiously for footprint analysis.

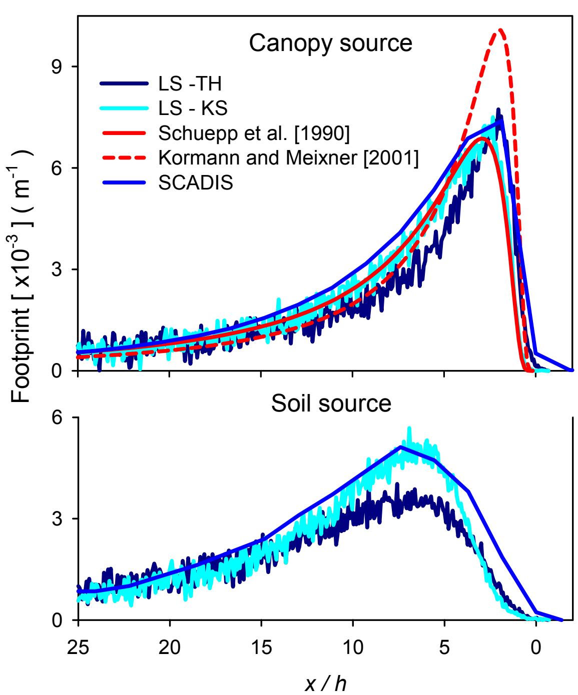

Figure 3. Predictions of flux footprint with the Lagrangian stochastic trajectory simulation of Thomson (1987) (LS-TH) and Kurbanmuradov and Sabelfeld (2000) (LS-KS), analytical solutions to the diffusion equation, and SCADIS model estimations of flux footprints above a managed forest plantation in Florida (z = 1.4h) in neutral conditions. (After Sogachev et al., 2005b).

3.2 *Effects of infinite gaps*

The model can be used for many practical tasks that require the knowledge of turbulent flow statistics. Our main concern is energy and surface-atmosphere scalar exchange in the presence of gaps inside a forest. Airflow heterogeneity induced by a forest edge can lead to a misinterpretation of the flux signal measured in the vicinity of the forest edge. Thus, Klaassen et al. (2002), (hereafter K2002) reported about energy balance closure as a function of fetch downwind of a forest edge. Observations were made above a forest at 150 m from a bog-forest transition on flat terrain. “Fetch” is here defined as distance between the measurement location and the forest edge into the wind direction, so variations in fetch arise from variations in wind direction. The data are presented in Figure 4a as normalized energy flux (N), defined as:

$$N = \frac{H + LE}{R - G}, \qquad (6)$$

where H is sensible heat flux, LE is the latent heat flux and L is the latent heat of vaporization of water; R is the net radiation and G is soil heat flux. In the case of equilibrium and perfect measurements of all energy fluxes, N should equal 1 over forest ($N = N_\infty = 1$). For fetches exceeding 400 m, K2002 found $N/N_\infty = 1.03 \pm 0.11$, or statistically not deviating from unity. For fetches between 150 and 400 m, $N/N_\infty = 1.16 \pm 0.06$ is characteristic for enhancement of turbulent fluxes. The enhancement of turbulent fluxes for short fetches has been explained by advection (K2002). Yet, surface heat fluxes of the upwind bog were even smaller than surface fluxes of the forest, implying that horizontal flux advection cannot explain the observed heat fluxes.

Klaassen and Sogachev (2006) were able to reproduce increased flux downwind of the forest edge using SCADIS model with input data extracted from K2002. LAD for the forest with the height of 20 m and LAI = 1.8 was approximated by analytical function from Markkanen et al., (2003). The parameter α describing the shape of the foliage distribution was fitted as 5; with increasing α more leaves are located near the top of the vegetation. Figure 4a shows the simulation result. Both measurements and simulations show $N/N_\infty > 1$ for fetches between 200 and 500 m downwind of the forest edge. The simulations show a gradual decrease of N/N_∞ towards unity for larger fetches, whereas the measurements suggest $N/N_\infty < 1$ for fetches around 700 m. A closer look at the measurement location revealed that the complex forest structure in the upwind direction may cause the difference between observations and simulation around 700 m fetch. The decrease of atmospheric scalar fluxes just behind the forest edge is still physically unexplained. This may have been caused by a decrease in the mixing length due to a locally enhanced dissipation rate of turbulent kinetic energy and, in turn, by a weak turbulent exchange here. There is insufficient information known about turbulent processes in this area to prove or rebut SCADIS model results.

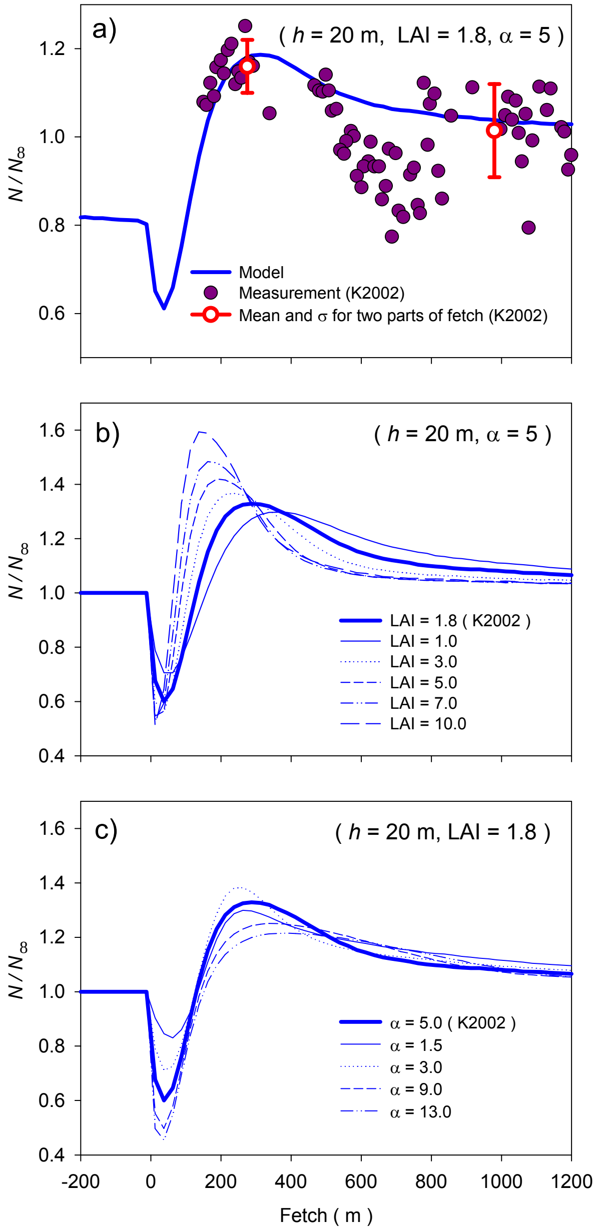

Figure 4. Normalized energy flux at 1.35 forest height h (27 m height) versus fetch downwind of the forest edge: a) for observed intensity of energy fluxes above the open place and the forest; for case when fluxes from the bog and forest are equal each other as a function of b) forest density and c) forest vertical structure. Negative fetch values are upwind of the forest edge. (After Klaassen and Sogachev, 2006).

The model was used to test whether enhanced atmospheric scalar fluxes might be a common feature downwind of a forest edge. The simulations have been done with upstream surface fluxes equal to forest fluxes for comparison purposes. General result of the sensitivity analysis is that height and fetch of enhanced fluxes are hardly sensitive to wind velocity and scale with forest height (not shown in figures). Figure 4b shows that the maximum enhancement of atmospheric flux increases with increasing forest density, but the fetch of enhancement decreases, as stronger coupling to denser forest results in a concentration of the plume of enhanced atmospheric fluxes to a smaller area downwind of the edge. Figure 4c indicates that the influence of leaf area density near the top of the forest canopy hardly affects the fraction of atmospheric flux arising from forest as any increase of nearby leaf area is compensated by a decrease of atmospheric mixing.

3.3 *Effects of confined gaps*

Sogachev et al. (2005b) used the model to explore the effect of clearcuts on footprints and flux measurements above a forest canopy. In contrast to Klaassen and Sogachev (2006), they considered CO_2 as a scalar and investigated its magnitude and its vertical flux distribution as well as flux footprints as function of clearcut width. As a testbed, measured flow statistics in the managed pine plantation of the Florida AmeriFlux site (Leclerc et al., 2003) were used. It was found that scalar fluxes are sensitive to clearcut widths. According to the technique described in Section 2.2, Sogachev et al. (2005b) estimated the footprint contributed by each source to the flux sensor. Footprint validation results were presented above in Figure 3. Illustrative examples of footprints derived by the model for joint contribution of sources located within the canopy layer and on the soil surface (net footprints) for the transect 17*h* wide are given in Figure 5. One can see that contribution from gaps to signal measured downwind of a forest edge is higher for tower located close to the edge and gradually disappear when tower shifts far downwind. At the distance more than 30*h* downwind of the forest edge footprint can be considered as one for homogeneous surface (Figure 3).

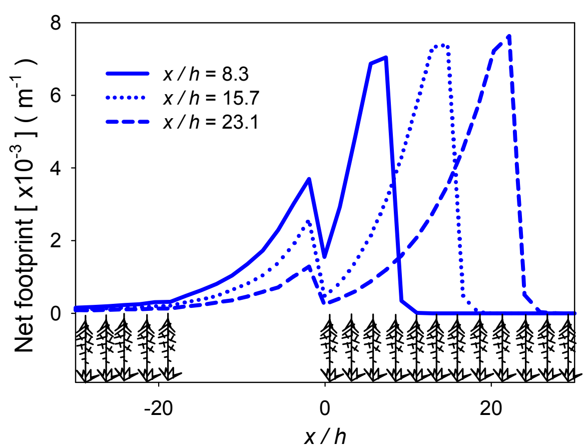

Figure 5. Examples of net footprints (joint contribution of sources located within the canopy layer and on the soil surface are considered) derived by the model for a case of 17h wide clearcut for sensors located at various normalized distances, x/h downwind of the forest edge at a height of 1.4h.(After Sogachev et al., 2005b).

The knowledge of the footprint itself considerably improves our ability to deconstruct a flux signal into its different source signatures. However, Sogachev et al. (2005b) pointed out that for purpose of establishment and siting of flux towers the information provided by the footprint function is more convenient if presented in another form. They introduced fractional flux function describing the contribution of given source into a signal at that imaginary flux tower. Figure 6 compares these fractional flux functions for measurement height $z = 1.4h$ obtained for the different modeled clearcut sizes. The behavior of these functions depends on the flow structure in the clearcut-forest transition zone, which in turn is defined by the canopy structure. The flow acceleration in the lower canopy and above, the flow deceleration in the upper canopy region together with the vertical air motions, all occurred in this zone resulting in a complicated distribution of the scalar field and vertical fluxes. With information on fluxes from the soil above the clearcut, above a forest (as might be seen during nighttime conditions with upward CO_2 fluxes for example) and from the forest canopy, net fluxes at given height downwind of the forest edge can be estimated.

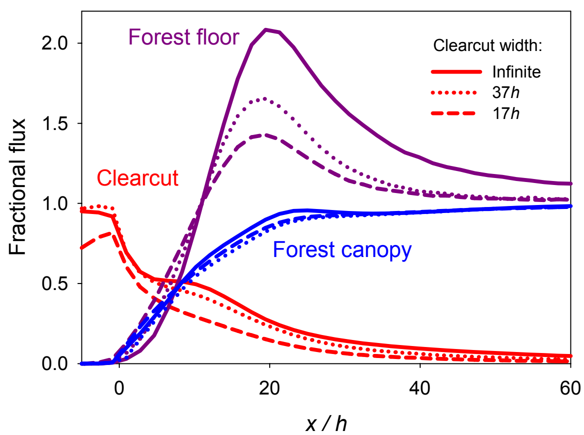

Figure 6. Variation of the fractional flux functions at a height of 1.4h with normalized distance, x/h downwind of the forest edge, derived by footprint modeling for sources on forest floor, inside a tree layer and on the clearcut. These functions describe the contribution of corresponding sources to a measured signal at an arbitrary location downwind of the clearcut-forest edge. (After Sogachev et al., 2005b).

3.4 *Advection in gaps*

As it was mentioned the knowledge of the footprint allows one the correct interpretation of a signal and, as a result, the correct estimation of net ecosystem exchange (NEE). NEE is defined as the flux through a horizontal plane at the height z_r, i.e. the exchange rate between the forest (including the soil) and the atmosphere. Errors in NEE estimates are introduced by the use of single-point measurements over a heterogeneous surface where the assumption of horizontal homogeneity is violated. Analytical and LS footprint models cannot be applied in this case.

An expression of NEE for scalar C in the mean wind coordinate (two-dimensional case) can be written (Wang et al., 2005):

$$NEE = F_0 + \int_0^{z_r} S dz$$

$$= \underbrace{\left(\overline{w'C'}\right)_{z=z_r}}_{[1]} + \underbrace{\int_0^{z_r} \frac{\partial C}{\partial t} dz}_{[2]} + \int_0^{z_r} \left[\underbrace{u\frac{\partial C}{\partial x}}_{[3]} + \underbrace{w\frac{\partial C}{\partial z}}_{[4]} + \underbrace{\frac{\partial \left(\overline{u'C'}\right)}{\partial x}}_{[5]} \right] dz \qquad (7)$$

where u and w are the mean velocity components in the horizontal (x, mean wind direction) and vertical (z) directions, respectively. F_0 is the flux cross the soil-air interface; S is the source term; $\overline{u'C'}$ and $\overline{w'C'}$ are the horizontal along-wind turbulent flux and vertical turbulent flux of C, respectively, and z_r is the height of the flux observation. Till recently, it has been in common practice to consider only terms [1] (vertical eddy flux at $z = z_r$) and [2], storage with all the other terms assumed insignificant due to horizontal homogeneity. The model presented allows us to quantify the real magnitude of advection terms in gaps.

Particular properties of different sites vary significant. Therefore, below numerical experiments have been done mainly for illustrative purpose. As input data for vegetation we used the same data as in previous Section from Florida AmeriFlux site (Leclerc et al., 2003). The width of clearcut was 37h as that in reality on this site. Radiation conditions typical for cloudless weather in February and geostrophic wind as 10 m s^{-1} were assumed. Figures 7 and 8 demonstrate balance components for two scalars CO_2 and temperature, respectively, derived by the model for the midday. These two scalars have different source locations and it is why under similar airflow conditions the model shows different structure of advective fluxes.

During the day, the underlying surface has CO_2 sources with opposite signs (see NEE in Figure 7): positive for clearcut (about 8 µmol m^2 s^{-1}) and negative for the vegetation canopy (about -23 µmol m^2 s^{-1}). It results in sharp contrast between CO_2 concentrations on the open place and the forest, and leads to horizontal advective fluxes [3] that are comparable with turbulent vertical fluxes [1] above the forest at both lee and windward sides of the forest (Figure 7). Vertical advective fluxes, [4] as well as horizontal diffusion, [5] are only minor importance there. As a result, fluxes that in reality could be measured by sensor located arbitrary along the considered transect deviate from real looked for fluxes above the whole clearcut and at the distance till 30h downwind of a windward side of the forest edge.

In contrast to CO_2 the heat has sources inside the clearcut and the forest with similar sign, but with slightly different intensity. It is because an open place and a forest are generally characterized by different Bowen ratios. Figure 8 shows that about midday only the horizontal diffusion [5] has a minor importance. Both horizontal [3] and vertical [4] advective terms can, in absolute values, equal the half of vertical turbulence flux intensity. At the lee of the forest they are slightly lower than those at the windward side of the forest. At both locations the vertical and horizontal advective fluxes have opposite sign and partly compensate effects of each other on resulted vertical flux. The fluxes measured and those looked for are approximately equal along transect. However, due to the streamwise and vertical velocity deviations adjust to the forest at different rates (Irvine et al., 1997) there is a shift between advective fluxes amplitudes and the heat flux measured downwind of the forest edge is a wave-like function of the fetch, with a maximum existed the real flux at some distance well back in the forest (14*h*). It is similar to that was observed by K2002.

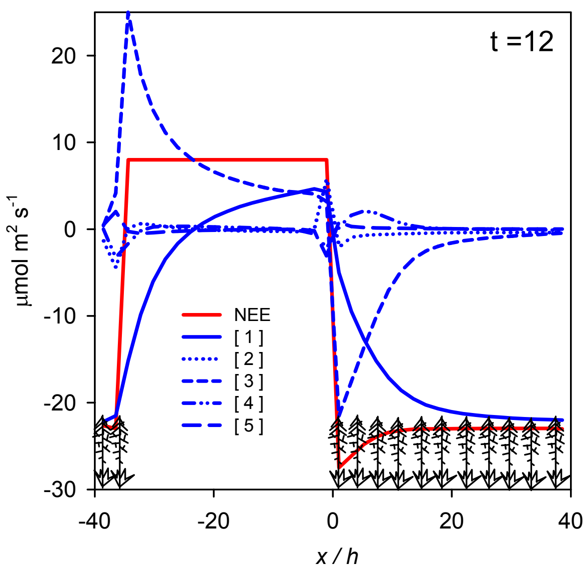

Figure 7. Variation of terms in equation (7) for CO_2 at the height of 1.4 h (z_r) with the normalized distance, x/h along the forest gap-forest transition zone. Terms [3]-[5] are integrated from z=0 to z=z_r. The forest gap width is 37h.

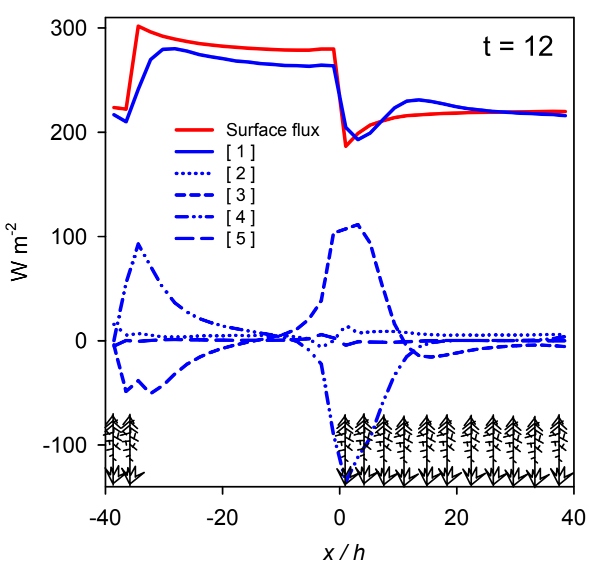

Figure 8. As in Figure 7, but for the heat.

4. CONCLUSIONS

There is a surprising omission in experimental studies pertaining to the transition at a forest edge considering that small areas of forested landscape are common. In contrast with the scale of field experiments required to examine the in-depth spatial variation of physical processes at these transitions needed for many practical applications, modeling is cost-efficient and most useful. The two-equation closure approach does not require a predefined mixing length and seems to be naturally suited to modeling atmospheric flows over heterogeneous surfaces. We use E –ω model modifying it to account for plant drag. The numerical experiments show that this modification works well.

Applications of the model are presented, namely the investigation of increased heat fluxes near a forest edge observed by Klaassen et al., (2002), study of effect of clearcuts on footprints and flux measurement at Florida site (Leclerc et al., 2003) and that of Sogachev et al. (2005b); estimation of the magnitude of advective fluxes caused by forest gaps. The results suggested that an adjustment in the momentum flux does not necessarily mean an adjustment in scalar flux. The flow distortion created by the forest edge produces complex flow motions that influence the scalar distribution. A simultaneous interaction of sources located on the surface and in the canopy layer can produce a net flux enhancement over different fetches, the amplitude and distribution of which is a function of the ratio of source strengths of the surface to that of the canopy layer. It is recommended to estimate surface fluxes of forest from atmospheric observations using expanded footprint models which take into account the turbulence structure the downwind forest edge.

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