Tellus (2008), 60B, 179–187
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Turbulence spectra, shear stress and turbulent kinetic energy budgets above two beech forest sites in Denmark

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(Manuscript received 30 December 2006; in final form 17 September 2007)

ABSTRACT

The focus of this study is the combined influence of the roughness sublayer (RSL) found above tall vegetation and the internal boundary layer (IBL) on the near-neutral flow above two forest sites. Measurements of the 3-D wind field from masts about twice the forest height were analysed. For both sites, influence from upwind conditions was detected for a short-fetch sector. For one of the sites, an additional long-fetch sector without significant IBL influence is presented. Spectral analysis, dissipation length scale analysis and evaluation of the most important terms in the turbulent kinetic energy and shear stress budgets, were performed. For all selected sectors, RSL influence was detected close to the canopy top: the dissipation length scale was greater than the height above the displacement height of the forest, and the turbulent transport terms were significant. For the short-fetch sectors, the spectral analysis of measurements taken in the RSL and in the IBL (above the RSL) showed that scaling by fixed length and velocity scales resulted in a good collapse of the spectral peaks. For the long-fetch sector, the RSL influence disappeared at greater heights, and the flow is nearly adjusted with the new surface.

1. Introduction

The turbulent mixing represents the most effective mechanism of momentum, energy and scalars exchange between land vegetation and atmosphere and our understanding of this process is thereby a key factor for assessing weather and climate dynamics. Turbulent motions over uniform vegetation stands and flat terrain are the best known and most investigated case, and now, thanks to numerous field and wind tunnel experiments, as well as numerical studies, the theoretical pattern of turbulent flows over such kind of forest canopies is quite well known and characterized (see Finnigan, 2000, for a review). On the other hand, the dynamics of flows over heterogeneous and patchy vegetation canopies is still a pending problem (Finnigan, 2000), mainly due to the scarcity of experimental results dealing with it.

In this study we analysed measurements from experiments over fetch-limited forests, where the flow is influenced from two types of deviations from the classical inertial sublayer description (for example, Monin–Obukhov similarity theory): (1) the roughness sublayer (RSL) and (2) the internal boundary layer (IBL).

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DOI: 10.1111/j.1600-0889.2007.00326.x

Over homogeneous surfaces with tall canopies, observations and theoretical considerations suggest that turbulence has different characteristics compared to low vegetation and that local equilibrium condition between production and destruction/dissipation of turbulence is not achieved inside and just above the canopy (Finnigan, 2000). Large coherent eddies, which have length-scales proportional to the canopy height and/or distance between the vegetation elements, dominate the transport of momentum, heat and mass. The region where these eddies dominate defines the RSL (Raupach et al., 1996) and depending on stand density, it can extend several canopy heights in the vertical.

Turbulence spectra measured inside the RSL do not follow the inertial sublayer scaling proposed by Kaimal et al. (1972). Instead the spectral peaks, measured at different levels show a good collapse using fixed length and velocity scales, for example, the canopy height h_c and the mean wind speed $\overline{u}_{hc}$, measured at the canopy top (Kaimal and Finnigan, 1994).

Measurements of shear stress and turbulent kinetic energy (TKE) budgets, undertaken both in field (Leclerc et al., 1990) and wind tunnel experiments (Raupach et al., 1986; Brunet et al., 1994), highlighted that it is the turbulent and pressure transport terms which are mainly responsible of the absence of local equilibrium condition inside the RSL.

The dynamics of turbulent motion becomes even more complicated for flows over heterogeneous and patchy tall vegetation stands. When air flows over changing terrain (forest edges or other roughness change), an internal boundary layer (IBL) develops over the new surface, growing in height with the distance downwind of the edge. In the lowest region of the IBL, often called the equilibrium layer (EL), it is supposed that a new constant-stress inertial sublayer has been achieved in local equilibrium with the new surface. Above the IBL height h_i, the flow is in equilibrium with the upstream surface. Between h_i and the EL's height h_e, there is a transition region, where the flow is not yet in local equilibrium with the new surface.

However, it is demonstrated that for transitions across forest edges "the growing EL has first to encompass the RSL, before any thickness of inertial sublayer can be developed" (Cheng and Castro, 2002). This means that considering some cases (like in urban areas and small forest canopies), an inertial (log-law) region matching the downstream surface may actually never develop in the available fetch.

Just downwind of the forest edge, where the flow adjusts to the new displaced surface, the relatively simple picture of the IBL/EL structure is not valid. In this so-called adjustment region which extends downstream of the forest edge for a distance $x_0 \approx 3L_c$, where $L_c = (C_d LAI/h_c)^{-1}$ is the canopy adjustment length (Belcher and Hunt, 2003), C_d the drag coefficient and LAI the leaf area index, the flow adjusts to the displaced surface of the forest. Even by using a relatively low value of $C_d = 0.2$ (Yang et al., 2006a) in the equation for x_0 derived by Belcher and Hunt (2003), the estimated length of the adjustment zone would not exceed more than 75 m into the forest. Hence, for this study, the immediate influence of the edge is considered negligible and the IBL/EL in combination with a RSL description is assumed sufficient.

The IBL growth over low vegetation has been studied mainly for relatively short fetches, as reviewed by Garratt (1990, 1997). A few experiments have investigated the transition associated with a forest edge. Raynor (1971) investigated the mean wind speed and temperature change associated with a pine forest edge using six masts between $x = -3h_c$ and $x = 10h_c$, where x is the distance from the forest edge. Gash (1986) estimated the growth of the EL at a heath-forest interface using several masts ranging far upstream of the forest ($x = -55h_c$) to well downstream into the forest ($x = 40h_c$). More recently Miller et al. (1991) investigated the flow structure in an Alpine forest clearing and Irvine et al. (1997) reported measurements near a forest edge. The Irvine et al. study used four masts where the focus area was close to the edge and the mast the furthest into the forest was located around $x \approx 15h_c$ inside the forest. The data presented by Irvine et al. has subsequently been used by Morse et al. (2002) for comparison with a wind tunnel data set and in Yang et al. (2006a,b) for comparison with a large eddy simulation study. The works by Yang et al. and Morse et al. extend their model and wind tunnel analysis up to $x \approx 15h_c$, corresponding to the Irvine et al. data set. In Morse et al., key terms of the streamwise and vertical variance prognostic equations were only calculated at the canopy top ($z = h_c$), because this was the only available height for estimating the vertical derivatives from the measurements, but Yang et al. (2006b) showed the vertical variation of the budget terms, reporting their model results up to $z = 4h_c$.

The combined influence of a RSL and an IBL on the atmospheric flow further inside the forest ($x/h_c > 20$) was the focus in Dellwik and Jensen (2005) for a real forest canopy and by Cheng and Castro (2002) for a wind tunnel experiment.

The aim of this study is to present and further discuss turbulence measurements taken above two fetch-limited beech forests at $x > 20h_c$. Using data from the same experiments, Dellwik and Jensen (2000, 2005) investigated the growth of the EL and the dimensionless wind and temperature flux profile relationships. Here, we extend the previous studies by including analysis of velocity spectra, the vertical variation of the dissipation length, and the vertical profiles of the most important terms in the shear stress and TKE budget. Field measurements of vertical profiles of shear stress and TKE budget terms above a fetch limited forest far away from the adjustment zone have not been reported in the scientific literature before.

2. Materials and methods

2.1. Sites and measurements description

2.1.1. Sorø. The Sorø site is located in an 85-year-old beech forest (55°29.19′N, 11°38.77′E) on the island Zealand, Denmark. The forest extends 1 km in the east-west direction and 2 km in the north-south direction. The area surrounding the forest is dominated by agricultural fields with the exception of a second small forest situated to the north-northeast. There is a 150–250 m corridor of farmland between the forests. The area is flat. The 57 m tall mast is located in the middle of the forest with a fetch of approximately 500 m both to the west and the east. The beech trees are on average 25 m tall, but the forest also contains scattered stands of conifers. Mean leaf area index for the main footprint of the forest is 5 m^2 m^{-2}. The leaf area index is approximately constant between June and September and drops slowly during the autumn. Displacement height and roughness length are $d = 20.6 \pm 4$ m and $z_0 = 1.8 \pm 0.7$ m (Dellwik and Jensen, 2005).

A number of both short term and longer-term field campaigns have been performed at the Sorø site. In this study data from a short field campaign in 1996 as well as a longer one in 2001 are used.

The experiment in 2001 included sonic anemometers (Solent 1012R2, Gill Instruments Ltd., Lymington, UK) at 43 and 31 m and a wind profile from 27 to 57 m taken with cup anemometers (Cup P2244, Risø National Laboratory, Denmark) and a wind vane at 57 m (also Risø National Laboratory, Denmark) registered the wind direction. This experiment is described in detail in Dellwik and Jensen (2005). With data from the 2001 experiment we analyse the influence of the fetch limitation from the western sector (Sorø W).

The 1996 experiment in Sorø, sonic anemometers (Solent 1012R2, Gill Instruments Ltd., Lymington, UK) were mounted at three levels above the forest (31, 43 and 55 m) and a wind profile was measured between 32 and 57 m with Risø cup anemometers. Analysis of this experiment was previously published in Dellwik and Jensen (2000). The 1996 experiment had a short duration and only a limited choice of wind directions was possible. From the 1996 experiment, we analyse the influence of the fetch limitation from the north sector (Sorø N).

The fetch lengths for Sorø W and Sorø N are approximately 500 and 2500 m respectively. For Sorø N, the fetch extends over the second forest mentioned above. However, the footprint area of the measurements in this sector will also include low-roughness farmland to the NW of the Sorø forest as well as the corridor of farmland between the two forests described above. A previous study has shown that this influence is likely to be small (Dellwik and Jensen, 2000). For fetches of 500 and 2500 m and near-neutral conditions, the EL height is estimated to 13 and 42 m above the displacement height respectively, using a EL height equation derived in Dellwik and Jensen (2000). This corresponds to 34 m for the Sorø W sector and to 63 m for Sorø N sector.

2.1.2. Corselitze. The Corselitze site was located in a 100-year-old beech forest on the east coast of the island Falster, Denmark (54°50.62′N, 12°09.13′E). The forest extends approximately 1-2 km in the east-west direction and 4 km in the north-south direction. The average height of the trees was in 1994 about 25 m, and the estimated values of the displacement height and roughness length are $d = 21$ m and $z_0 = 1.6$ m. A lower value for d was published in (Dellwik and Jensen, 2000), but this value was on reevaluation found to be erroneous.

A 57 m tall mast was located in the northern part of the forest with the minimum fetch of 500 m to the east. The experiment lasted from the end of March to the middle of May 1994. The terrain is flat, except for a a step-change of terrain elevation of approximately 10 m at the coastline. The influence from this dramatic change of elevation is however estimated to be negligible at the measurement site (Jensen et al., 1990).

The mast was instrumented with two sonic anemometers (Solent 1012R2, Gill Instruments Ltd., Lymington, UK) at 40 and 53 m height and Risø cup anemometers at 32, 37, 45 and 57 m. A Risø wind vane was mounted at 57 m. In this study, we analyse data from the north-eastern/eastern sector corresponding to an average fetch value of 550 m. The EL should then extend approximately 34 m above ground (Dellwik and Jensen, 2000). No leaf area index measurements were performed at Corselitze, but, due to similarities in the stands, it is estimated to be similar to the leaf area index in Sorø.

2.2. Turbulent kinetic energy and shear stress budgets

For a near-neutral steady-state two-dimensional flow, the governing equation of the TKE is (Eq. 4.28 Kaimal and Finnigan, 1994)

$$\frac{\partial \overline{e}}{\partial t} = 0 = \underbrace{-\overline{u'w'}\frac{\partial \overline{u}}{\partial z}}_{\mathbf{P}} - \underbrace{(\overline{u'^2} - \overline{w'^2})\frac{\partial \overline{u}}{\partial x}}_{\mathbf{P_n}} - \underbrace{\left[\overline{u}\frac{\partial \overline{e}}{\partial x} + \overline{w}\frac{\partial \overline{e}}{\partial z}\right]}_{\mathbf{A}} - \underbrace{\left[\frac{\partial \overline{u'e}}{\partial x} + \frac{\partial \overline{w'e}}{\partial z}\right]}_{\mathbf{T_t}} - \underbrace{\frac{1}{\rho}\left[\frac{\partial \overline{u'p'}}{\partial x} + \frac{\partial \overline{w'p'}}{\partial z}\right]}_{\mathbf{T_p}} - \underbrace{\epsilon}_{\mathbf{D}} \quad (1)$$

where $\overline{e} = 0.5(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$. In the eq. (1), the right hand-side terms are, in order, the shear production (P), the normal stress production ($\mathrm{P_n}$), advection (A), turbulent transport (T_t), pressure transport (T_p) and dissipation (D).

Under the same assumptions made for the eq. (1), the shear stress budget can be written as

$$\frac{\partial \overline{u'w'}}{\partial t} = 0 = \underbrace{-\overline{w'^2}\frac{\partial \overline{u}}{\partial z}}_{\mathbf{P_{SS}}} - \underbrace{\left[\overline{u}\frac{\partial \overline{u'w'}}{\partial x} + \overline{w}\frac{\partial \overline{u'w'}}{\partial z}\right]}_{\mathbf{A_{SS}}} \underbrace{-\left[\frac{\partial \overline{u'^2w'}}{\partial x} + \frac{\partial \overline{u'w'^2}}{\partial z}\right]}_{\mathbf{T_{SSt}}} - \underbrace{\frac{1}{\rho}\left[\frac{\partial \overline{w'p'}}{\partial x} + \frac{\partial \overline{u'p'}}{\partial z}\right]}_{\mathbf{T_{SSp}}} + \underbrace{\overline{p'\left(\frac{\partial u'}{\partial z} + \frac{\partial w'}{\partial x}\right)}}_{\Phi} \quad (2)$$

where the right hand-side terms represent shear production ($\mathrm{P_{SS}}$), advection ($\mathrm{A_{SS}}$), turbulent transport ($\mathrm{T_{SSt}}$), pressure transport ($\mathrm{T_{SSp}}$) and pressure-strain (destruction) (Φ).

In the eqs. (1) and (2) the terms, which include the viscosity (viscous transport and dissipation), do not appear in the budgets, since they have been assumed negligible (Lumley, 1970). Reynolds average statistics up to the third order moments in the terms P, $\mathrm{P_{SS}}$ and the vertical components of T_t and $\mathrm{T_{SSt}}$ have been calculated from the sonic anemometer measurements using an averaging time of one hour. No detrending was applied, but the periods were accurately chosen one by one in order to check the stationarity.

Before the calculation of the turbulent statistics, spurious spikes were removed from the raw data by visual inspection and a standard 2-D coordinate rotation for the wind components was applied (Kaimal and Finnigan, 1994). The finite difference scheme was used to derive all vertical derivatives in the budget equations for a point midway between two measurements levels. Cup anemometer data also have been used to estimate the vertical gradient $\partial \overline{u}/\partial z$ in the shear production term P.

TKE dissipation rate ϵ was estimated from power spectral density measurements, as described below.

The horizontal components of TKE turbulent transport ($\overline{u}\partial \overline{e}/\partial x$) and shear stress turbulent transport ($\partial \overline{u'^2w'}/\partial x$) are normally assumed to be much smaller (Kaimal and Finnigan, 1994) and however they cannot be calculated.

The other terms in the eqs. (1) (A, T_p and P_n) and (2) (A_{SS}, T_{SSp} and Φ) cannot be evaluated from our measurements, and their possible contribution will be inferred indirectly, discussing results found in the literature.

2.3. Turbulent spectra and TKE dissipation rate

Turbulent spectra of u and w wind components have been calculated for the selected runs (see Section 2.4) using fast Fourier transform (FFT) on segments of 2^{15} data points, which corresponds to about 54 minutes.

In the inertial subrange the spectra takes the form $nE_{u,w} = \alpha_{u,w}\epsilon^{2/3}(2\pi n/\overline{u})^{-2/3}$ where ϵ is the TKE dissipation rate, n is the frequency in Hz, and we adopted the Taylor's hypothesis of frozen turbulence. A value of 0.52 for the Kolmogorov constant α_u is used (Kaimal et al., 1972), and the local isotropy relation for $\alpha_w(=4/3\alpha_u)$. The streamwise component of the eq. (2.3) was used to estimate the dissipation rate ϵ at all measurement levels for each data set.

2.4. Data selection criteria

In this study, the analysed periods were selected from the three data sets (Sorø W, Sorø N and Corselitze) as reported in Table 1. For the Corselitze and Sorø W data sets, the wind direction sectors were selected to represent short fetch conditions. Average values of the normalized fetch length x/h_c were 20 for Sorø W and 22 for Corselitze (north-east/east sector). The small difference of fetch length values does not influence our results, since we are well far from the edge, where the horizontal non-homogeneity of the flow is larger. The Sorø N sector has a normalized fetch length of $x/h_c \approx 100$, and it represents the long fetch condition in this study. For the sectors chosen for analysis, the tower structures could not affect the measured wind field.

Only near-neutral cases were investigated and the Obukhov length $L = -u_*^3/(\kappa\beta\overline{w'\theta'})$ was chosen as stability parameter, where $u_* = \sqrt{-\overline{u'w'}}$ is the friction velocity, $\kappa = 0.4$ the von Karman constant, $\beta = g/T_0$ the buoyancy parameter, g the acceleration due to gravity, T_0 is a reference value of absolute temperature and $\overline{w'\theta'}$ the kinematic heat flux. The near-neutral cases were selected using the stability criterion $|[(z-d)/L]_1| < 0.05$, where the subscript 1 refers to the lowest level above the canopy. In Table 2, we reported the mean values and std of $[(z-d)/L]_1$ for each data set.

Table 2. Bin average (and standard deviation) values of flow conditions for the analysed data sets. The subscripts 1 and 2 refer to the measurement levels 31 and 43 m for Sorø W and Sorø N, and 40 and 53 m for Corselitze

Data set	$[(z-d)/L]_1$	u_{*2}/u_{*1}
Sorø W	−0.006 (0.013)	0.92 (0.08)
Sorø N	−0.016 (0.007)	0.96 (0.06)
Corselitze	0.007 (0.03)	0.85 (0.05)

Using these selection criteria, a limited number of runs of high-quality data were used for the present analysis (see Table 1).

3. RESULTS

3.1. The friction velocity ratio

The ratios of u_*, measured at 43 and 31 m for Sorø W and Sorø N, and at 53 and 40 m for Corselitze are reported in Table 2. The friction velocity ratio has often been used as an indicator of IBL influence (Jegede and Foken, 1999; Dellwik and Jensen, 2000). In general, a vertical divergence of momentum flux can be determined also by others factors, like the non-homogeneity of forest stand (clearings, patches with different height of the trees) as well as the presence of slopes in the footprint area. However in our case for the selected wind direction sectors, the height of the tree tops is relatively constant with no clearings in the closest 500 m of the mast, and the terrain is flat. For the selected periods, while the vertical variation of u_* was almost negligible for the long fetch run (Sorø N), a mean value ratio of 0.92 and 0.85 was found for the short fetch data sets (Sorø W and Corselitze).

3.2. The turbulent velocity spectra

Figure 1 shows the average velocity spectra E_u and E_w, computed at several levels for each data set. All spectra exhibit a well-defined inertial subrange, with a −2/3 slope spanning nearly two decades for u and about one decade for w.

As could be expected, the surface layer scaling does not work properly above a forest and the spectral peaks and the inertial subrange do not scale with u_* and $z-d$. In the roughness sublayer the local equilibrium between the TKE production and

Table 1. Overview of experiments and sites

Data set	Duration of experiment	h_c (m)	x/h_c	LAI (m^2 m^{-2})	No of selected runs (1 hour)
Sorø W	2001 − 07 − 30–2001 − 10 − 31	25	∼ 20	5	23
Sorø N	1996 − 09 − 07–1996 − 09 − 13	24.5	∼ 100	5	15
Corselitze	1994 − 05 − 03–1994 − 05 − 14	25	∼ 22	5	15

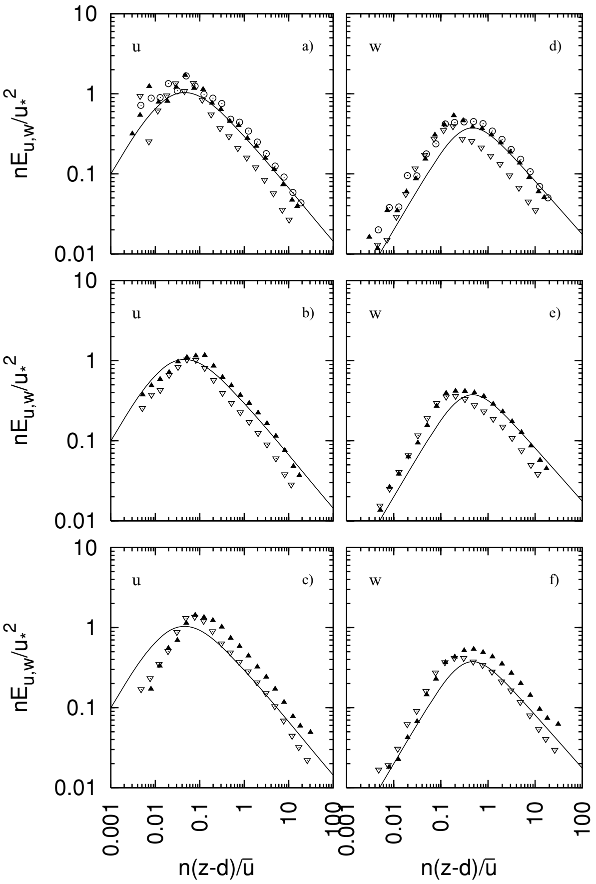

Fig. 1. Average spectra of streamwise and vertical velocity components, normalized with the surface layer scaling, for Sorø N (a,d), Sorø W (b,e) and Corselitze (c,f). In (a, d) the symbols refer to spectra measured at z = 31 m (down open triangle), z = 43 m (up full triangle) and z = 55 m (open circle). In (b,e) z = 31 m (down open triangle) and z = 43 m (up full triangle). In (c,f) z = 40 m (down open triangle) and z = 53 m (up full triangle). The solid lines are the surface layer reference curves from Kaimal et al. (1972).

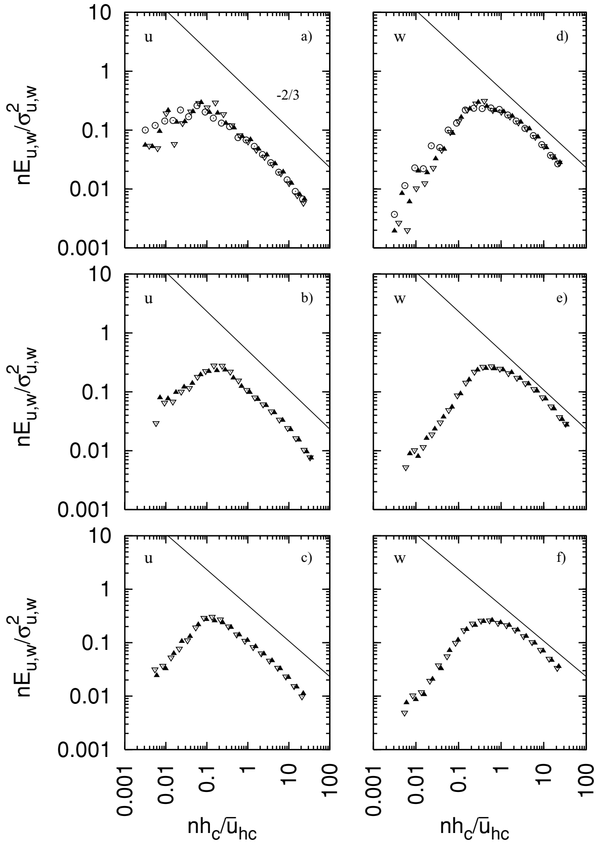

Fig. 2. Average spectra of streamwise and vertical velocity components, normalized with the canopy scaling, for Sorø N (a,d), Sorø W (b,e) and Corselitze (c,f). The symbols as in Figure 1.

dissipation is violated and the turbulent transport term is important (Kaimal and Finnigan, 1994). For the short fetch runs (Sorø W and Corselitze in Figs. 1b,e and 1c,f respectively), an apparent shift of spectral peaks to higher frequencies is notable moving from the lower to the upper measurement levels. Considering the long fetch run (Sorø N in Figs. 1a and d), the spectra measured at 43 and 55 m show a good collapse, suggesting that the flow, measured far from the canopy top, reached a local equilibrium in this case.

Figure 2 shows the velocity spectra, normalized by the canopy scaling (i.e. using the wind speed at canopy top $\overline{u}_{hc}$ and the canopy height h_c). This scaling gives a good collapse of the spectral peaks as well as of the inertial subrange, as reported by many authors (Raupach et al., 1986; Brunet et al., 1994; Amiro, 1990) for the RSL. The nE_u spectra peak at normalized frequency of 0.15 for all data sets, except Sorø N for which a bit smaller value was found. The vertical component of spectra peaks at normalized frequency of 0.45 for all data sets. These values are broadly in agreement with those previously found above canopies (Kaimal and Finnigan, 1994).

3.3. *TKE dissipation rate and dissipation length scale*

Since this study only concerns neutral atmospheric stratification, we do not show any stability dependence of the calculated TKE dissipation function $\Phi_\epsilon = \epsilon\kappa(z-d)/u_*^3$.

Near-neutral estimated values of Φ_ϵ are reported in the Table 3 for each data set. Although standard deviations for each bin are not small, in some cases the average values of Φ_ϵ are quite different from one (the expected similarity value). Close to the canopy top Φ_ϵ is less than one (especially evident for Sorø N and W), indicating the RSL influence (Lee, 1996). At upper levels, the Φ_ϵ values are larger than one (in particular for Sorø W and Corselitze runs, which represent short fetch situations), due to the IBL effect. As will be shown in the next section, the main mechanism responsible for this departure from the

Table 3. Bin average (and standard deviation) local values of the dissipation functions Φ_ϵ, *calculated from the analysed data sets. The subscripts 1 and 2 are as in Table 2, and the subscript 3 refers to z=55 m for Sorø N data set*

Data set	$\Phi_{\epsilon 1}$	$\Phi_{\epsilon 2}$	$\Phi_{\epsilon 3}$
Sorø W	0.54 (0.05)	1.24 (0.33)	–
Sorø N	0.54 (0.10)	0.93 (0.20)	1.12 (0.22)
Corselitze	1.09 (0.19)	2.25 (0.58)	–

similarity value is due to the contribution of TKE turbulent transport above a vegetated surface, leading to a pronounced imbalance between TKE production and dissipation.

Using the estimated dissipation rates, we calculated a dissipation length scale $L_\epsilon \equiv (-\overline{u'w'})^{3/2}/\epsilon$ for all data sets. According to Monin–Obukhov similarity theory, this length scale should vary as $L_\epsilon = \kappa z$ in the near-neutral homogeneous surface layer. In Fig. 3 the ratio $[L_\epsilon/(\kappa(z-d))] - 1$ is plotted against height, thereby illustrating the deviation from the equilibrium value of unity. Close to the canopy top ($z/h_c \approx 1.2$), L_ϵ is larger than $\kappa(z-d)$, indicating that the characteristic length scale of the eddies does not scale with height above the displacement height, as frequently has been found from many measurements undertaken in the roughness sublayer (e.g. Kaimal and Finnigan, 1994).

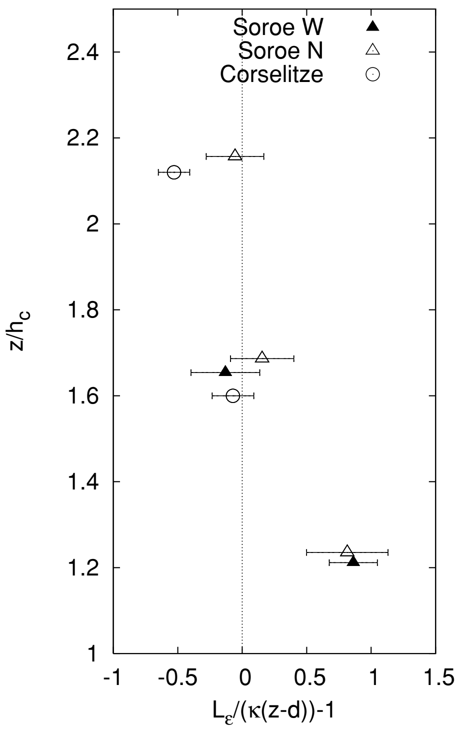

Fig. 3. Vertical variation of the dissipation length scale L_ϵ, calculated for Sorø W (full triangle), Sorø N (open triangle) and Corselitze (open circle). The bars are the standard deviation.

At greater values of z/h_c, the dissipation length scale tends to approach the equilibrium value for the long fetch case Sorø N. For Sorø W $L_\epsilon < (\kappa(z-d))$ at $z/h_c = 1.65$, which suggests IBL influence on the flow. For Corselitze, the near-equilibrium value close unity taken at $z/h_c = 1.6$ could illustrate the transition from the RSL ($L_\epsilon > (\kappa(z-d))$) to the IBL ($L_\epsilon < (\kappa(z-d))$) rather than implicating a true equilibrium condition. For Corselitze $z/h_c = 2.1$, the IBL influence is dominating as expected. This last result is in agreement with the wind tunnel data (Antonia and Luxton, 1971) and model predictions (Rao et al., 1974; Wood, 1978) for a smooth-to-rough transition.

To summarize the results shown in Fig. 3, the characteristic length scale of the eddies is approximately constant with the height for the short fetch runs (Sorø W and Corselitze), and tends to recover its surface layer value for the long fetch run (Sorø N), as we move far from the canopy top. These results are in good agreement with the turbulence spectra behaviour.

3.4. *Budgets for turbulent kinetic energy and shear stress*

In this section we present the TKE and shear stress budgets for Sorø W, Sorø N and Corselitze data sets, using the same selection criteria previously described (Tables 1 and 2). All terms were normalized by h_c/u_*^3 and vertical profiles were plotted as average values with one standard deviation error bars. Without any measurements of unperturbed upwind flow, we used the values of u_*, measured at the lower available level, assuming that they are roughly in equilibrium with the new downwind surface conditions, and considering that the structure of the two beech forest sites is very similar in terms of density and height of the trees and leaf area index.

3.4.1. TKE budget. Figure 4 shows the profiles of TKE budget terms calculated for the selected runs. Far from the canopy top ($z/h_c > 2$), the dissipation is almost twice the shear stress production. Balance between dissipation and shear stress production exists at about $z/h_c = 1.7$ and the turbulent transport gives a very small contribution. Near the canopy top the estimated values of turbulent transport are significant, and the shear production is larger than dissipation.

The last result is in agreement with the findings of several field and wind tunnel experiments above canopies (Raupach et al., 1986; Brunet et al., 1994; Leclerc et al., 1990), mainly showing that within the RSL (say, $1 < z/h_c < 2$) the turbulent transport acts as a sink of TKE, maintaining most of the turbulence in the lower part of the canopy.

For the long fetch run (open triangle) the magnitude of the shear production and dissipation terms, estimated far from the canopy top ($z/h_c > 1.6$) is a bit smaller than the short fetch values, indicating again that at these levels the flow responds to different forcing (surface layer for Sorø N and IBL influence for Sorø W and Corselitze). Approaching the canopy top all budget terms, estimated for different fetch conditions, show similar values, as they are mainly determined by the RSL influence.

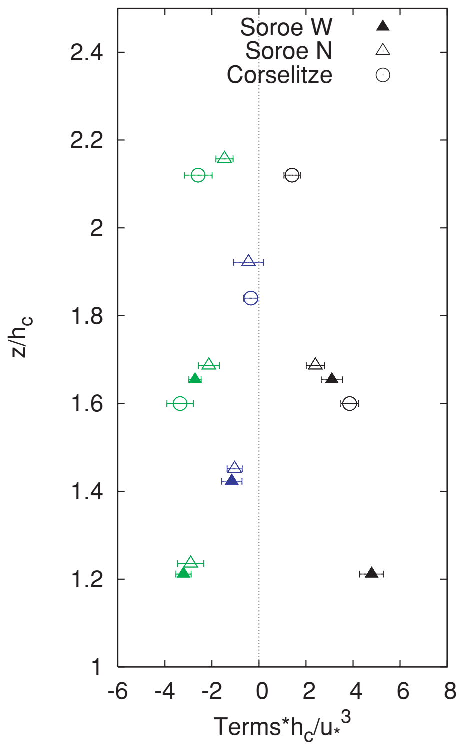

Fig. 4. Average values of the normalized TKE budget terms, calculated for Sorø W (full triangle), Sorø N (open triangle) and Corselitze (open circle). The terms are the shear production (black), dissipation (green) and turbulent transport (blue). The bars are the standard deviation.

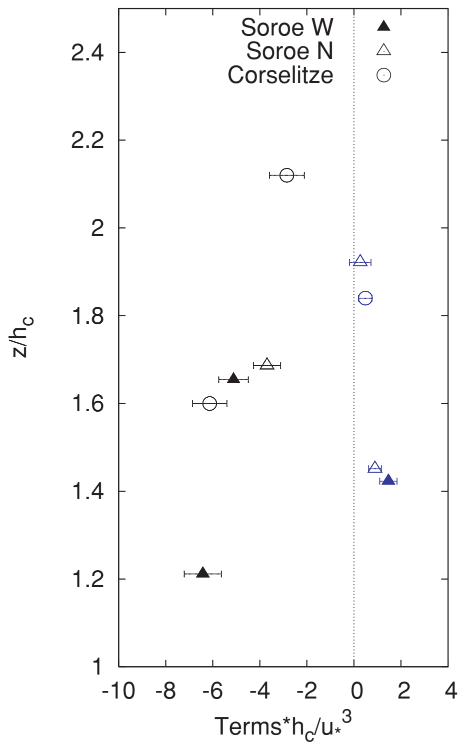

Fig. 5. Average values of the normalized shear stress budget terms: Shear production (black)and turbulent transport (blue). The symbols as in Fig. 4. The bars are the standard deviation.

3.4.2. Shear stress budget. Shear production indicates the production of Reynolds stress by the interaction of vertical velocity variance and the mean wind shear. According to previous studies (Brunet et al., 1994), the estimated values of P_{SS} are very large just above the canopy and then decrease moving far from the canopy top (Fig. 5). The turbulent transport term represents the vertical transport of $\overline{u'w'}$ to or from other layers. As shown in Fig. 5, this term is a source (positive values), which is significant in the RSL increasing as we approach the canopy top, according to (Raupach et al., 1986; Brunet et al., 1994; Leclerc et al., 1990).

4. DISCUSSION

4.1. The friction velocity ratio and the turbulent velocity spectra

Despite slightly different selection criteria, the friction velocity ratios for Sorø N and Corselitze agree well with the values published in Dellwik and Jensen (2000). The friction velocity ratio for Sorø W of 0.92 confirms the presence of IBL influence for this sector which was also found in the ϕ function analysis presented in Dellwik and Jensen (2005).

Spectral results showed the success of canopy scaling through the overall analysed vertical domain. In general, above a canopy forest one could expect the presence of two layers. The region just above the roughness elements is characterized by large coherent eddies with length scales proportional to the canopy height and advected downwind with a velocity proportional $\sim 1.8\overline{u}_{hc}$ (Finnigan, 1979). Further from the canopy top the flow should recover the surface layer properties (as in our long fetch run or/and in general for horizontally homogeneous conditions) or it should respond to the upwind perturbations (as in our short fetch runs). The fact that in the presented results the canopy scaling works well aloft (where the IBL features should dominate) highlights that these canopy-scale eddies develop downwind of the edge and dominate the turbulent structure up to a considerable height.

4.2. TKE and shear stress budgets

Only few studies above fetch limited canopies have reported results on TKE budget, and most of them focusing on the zone close to the forest edge. Vertical profiles of TKE budget from our measurements share a great similarity with those from Yang et al. (2006b), who employed a LES model. They showed the vertical profiles of TKE budget terms at several values of the normalized fetch length x/h_c. The shapes and magnitudes of our budget profiles for short fetch runs (Sorø W and Corselitze) largely agree with the Yang et al. (2006b) results at $x/h_c = 16$ (their Fig. 7). In particular, the shear production term is the largest term; the turbulent transport term acts as a sink just above the canopy and it has very small values aloft. Finally we noted that the Yang et al. turbulent transport becomes positive moving far from the canopy top, which is in agreement with the experimental results found for a smooth-rough change over low roughness elements (Kaimal and Finnigan, 1994). Unfortunately, from our measurements we were unable to assess the sign reverse, because no estimates of turbulent transport term were available at higher levels.

Yang et al. (2006b) reported also the advection and pressure terms, which give an important contribution only close to the edge, but they are much smaller at $x/h_c = 16$.

Using wind tunnel data and the data set of Irvine et al. (1997) field experiment, Morse et al. (2002) presented the key terms for the streamwise and vertical velocity variance prognostic equations at $z/h_c = 1$. They showed that, well back from the edge (their case of $x/h_c = 14.5$), the shear production was the dominant term, which had similar values reported by several studies (Leclerc et al., 1990; Meyers and Baldocchi, 1991) above a homogeneous canopy. This result fits very well with our finding and however it is not surprising, because at such level the flow is fully adjusted (i.e. indistinguishable from flow over an infinite forest) and it is totally characterized by the RSL dynamics. Moreover Morse et al. (2002) found that the normal stress production was significant, although an order of magnitude smaller than the shear production term. The other terms gave very small contribution for $x/h_c = 14.5$. Unfortunately they were unable to measure the dissipation rate from their measurements, due to changes in the slope in the inertial subrange of the spectra.

Kaimal and Finnigan (1994) reported the profile of TKE budget terms for a smooth-rough roughness change, using wind tunnel data of Antonia and Luxton (1971). The shear production was the larger source terms in the overall IBL. The turbulent transport was also a source, except near the surface where it assumes negative values as in the RSL above canopies. The advection had the largest negative values in the transition layer, far from the surface. The normal stress production was a source term, but much smaller than the shear production. Similar results were found by Castro et al. (2006) from wind tunnel measurements representing turbulence over urban-type roughness.

Studies of the shear stress budget over fetch limited forest have not been reported in the published literature, and, therefore, a test of our results is difficult, also because of well-known experimental limitations of direct evaluation of some of the budget terms. The unknown terms in the eq. (2) are the advection, pressure transport and pressure destruction. These terms are difficult to measure experimentally. In a wind tunnel study of a model canopy, Brunet et al. (1994) inferred (using some closure assumptions for the pressure terms) that the pressure strain Φ is the major component above an homogeneous canopy and the one mostly responsible of shear stress destruction. The pressure transport appeared opposed to turbulent transport just above the canopy.

Shear stress budget for a smooth-rough transition were studied by Antonia and Luxton (1971) in a wind tunnel and by Lin and Glendening (2002) using a LES model. Antonia and Luxton (1971) found that inside the IBL the advection can be significant at small fetches and mainly aloft where the flow is not fully adjusted with the new surface. The LES study showed that, for fetches similar to our cases, the advection and turbulent transport terms are of comparable magnitude, but are much smaller than the shear production and pressure destruction.

5. Conclusions

While there is a plenty of field measurements of turbulence statistics in the RSL over homogeneous surfaces with tall canopies, vertical profiles of second and/or higher order velocity moments above heterogeneous forests are very scarce. This was the main motivation of the present study. Turbulence data, measured above two beech forests with non-uniform fetch conditions, have been presented. Near-neutral data were selected, and the vertical variation of the turbulent flow characteristics have been analysed for short and long fetch conditions. The analysis highlighted the presence of different layers, in which the flow responds to different local and non-local forcing. While for the short fetch sectors (Sorø W and Corselitze) the flow is characterized by the combined influence of the roughness sublayer and IBL, the analysis of the long fetch sector (Sorø N) disclosed far from the canopy top (say $z/h_c > 1.6$) the presence of a layer, where the traditional surface layer scaling is valid.

The presented results were based on a consistent set of field measurements. Such data can provide further validation of the large eddy simulation approach, which already allows us the possibility to really study transitions across changes in land cover and the influence on turbulent fluxes. The presented results underline the need for the further development of theory, measurements and simulations to deal with non-equilibrium effects. In particular similar analysis and attempts to measure local and non-local effects above fetch limited forests should be also extended to measurements of passive scalars and other trace gases.

6. Acknowledgments

The study was supported by EU project Carboeurope and Nordic Centre of Excellence NECC. The authors want to thank the anonymous reviewers for their comments and helpful suggestions which improved the manuscript.

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