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# Sudden distortion of turbulence at a forest edge

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## Abstract.

Dellwik et al. (2013) presented data from a forest edge experiment based on two meteorological towers instrumented with sonic anemometers. The experiment was performed at a dense edge of the Tromnæs Forest, which is a 24 m tall mature beech stand on the island Falster, Denmark. The topography at the site is flat. The towers were placed approximately 1.5 canopy heights upwind and downwind of the edge, respectively, and were two canopy heights tall. For near-neutral, near-perpendicular flow towards the edge, one finding concerned that although the wind speed gradients were similar before and after the edge, the momentum flux was strongly reduced above the canopy. This is contrary to the results by standard Reynolds' averaged Navier-Stokes models that predict an overshoot of the momentum flux. Further, a reduction of the vertical variance of the flow was largely compensated by an increase in the lateral variance, whereas the streamwise variance remained approximately constant. This result is in contrast to the predictions by homogeneous rapid distortion theory. We apply and develop an alternative framework based on inhomogeneous rapid distortion theory, also called blocking, in combination with the turbulence model by Mann (1994), and investigate whether this model can predict the observed changes of the flow. The presented results are relevant for understanding the rapid changes of turbulence in the heterogeneous landscape.

## 1. Introduction

The investigation of how the mean wind field and turbulence are affected by the heterogeneous landscape is a fundamental research area in micro-meteorology. For wind turbine siting, the effects of tall forest canopies on the flow is of particular interest as the high shear and turbulence levels characteristic for large-scale forest effects (e.g. Bergström et al., 2013) may cause excessive loads on the turbine. In this study, we investigate whether the theoretical framework of *sudden blocking* (Hunt and Graham, 1978) can be applied to increase our understanding of how a dense forest edge affects the turbulent components of the near-surface flow. The study is a continuation of Dellwik et al. (2013), which showed that the vertical wind fluctuations and the vertical flux of horizontal momentum were suppressed over the canopy right after the edge, while the transverse fluctuations were increased.

## 2. Experiment

The experiment at the Tromnæs forest edge on the island Falster, Denmark, is described in detail in Dellwik et al. (2013). The data presented here were measured with Metek USA-1 sonic anemometers on two 45.9 m tall meteorological towers on either side of the dense forest edge, see figure 1. The distance to the edge from the masts were 35 m (M1 outside forest) and 37 m (M2 inside forest). The forest was at the time of the experiment in 2008 approximately 24 m tall.



The M1 tower outside the forest was instrumented with sonic anemometers at 11.9, 20.9, 30.9 and 45.9 m height. Inside the forest, the M2 sonic anemometers were located at 6.9, 11.9, 18.9, 24.9, 28.9, 36.9 and 45.9 m. Data were sampled at 20 Hz and block averaged over 10 minutes. Data were rotated into the streamline by requiring that  $V = W = 0$ , where  $V$  and  $W$  are the block averaged transversal and vertical velocity, respectively. This is different from the results presented in Dellwik et al. (2013), where the data were presented in a fixed Cartesian coordinate system, in which  $W$  coincides with the true vertical.

The Obukhov length  $L$ , was calculated as

$$L = -\frac{u_*^3 \Theta_S}{\kappa g \langle w \theta_S \rangle}, \quad (1)$$

where  $u_*$  is the friction velocity,  $\Theta_S$  is sonic temperature,  $\kappa = 0.4$  is the von Kármán constant,  $g = 9.82 \text{ ms}^{-2}$  the acceleration due to gravity and  $\langle w \theta_S \rangle$  is the sonic anemometer temperature flux which is approximated as the buoyancy flux. The friction velocity is defined by  $u_* = (\langle uw \rangle^2 + \langle vw \rangle^2)^{1/4}$ , where  $\langle uw \rangle$  and  $\langle vw \rangle$  are the vertical and transversal turbulent momentum fluxes, respectively. Capital letters refer to the mean, while lower-case letter are the fluctuations around the mean.

### 2.1. Data selection

Data were selected according to match near-neutral, near-perpendicular towards the edge, by using:

- $-0.1 < z_{\text{ref}}/L_{\text{ref}} < 0.07$
- $270^\circ < \theta < 290^\circ$ ,

where the ref subscript refers to the 30.9 m level measurement on M1.

Further, the criterion  $10 < U_{\text{ref}} \leq 11 \text{ m/s}$  was applied, to remove uncertainties on the near-canopy flow regarding wind speed dependence (also described in Dellwik et al., 2013). This selection left 39 ten minute samples at mean wind speed  $U_{\text{ref}} = 10.4 \text{ m/s}$ . Mean profiles compared with RANS calculations are shown on figure 2. The largest difference between model and measurements is seen right over the canopy, where the wind speed changes more smoothly in the RANS model than in the measurements. These differences will not be discussed here.

### 2.2. Coordinate systems

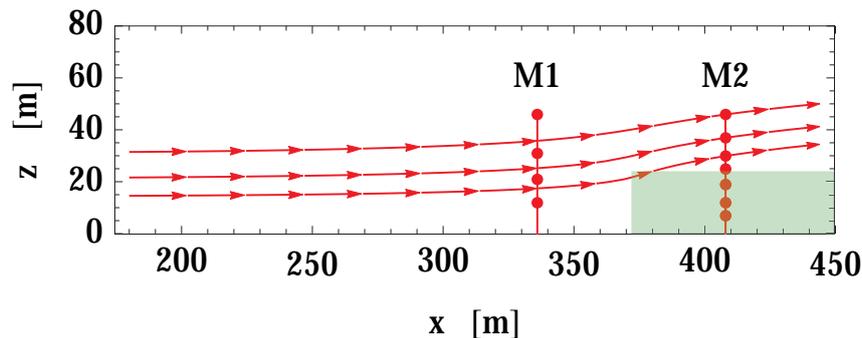
Assuming a two-dimensional mean flow for the case of winds perpendicular to the forest edge and incompressibility, it is possible deduce the vertical displacement of the mean streamlines from mast M1 to M2. Let  $U_1$  be the mean horizontal velocity at M1 and  $U_2$  at M2. Then continuity implies that the horizontal flow below a given streamline should be the same on both masts. In other words

$$\int_0^{z_1} U_1(z) dz = \int_0^{z_2} U_2(z) dz, \quad (2)$$

where  $z_1$  is the height of the streamline at M1 and  $z_2$  the height of the same streamline at M2 (see figure 1). The connection between  $z_1$  and  $z_2$  is solved in practice by differentiating (2) with respect to  $z_1$ :

$$U_1(z_1) = \frac{dz_2}{dz_1} U_2(z_2) \quad (3)$$

and obtaining the relation from the measured and smoothly interpolated wind profiles and numerical integration of (3). The results for the streamline heights for the top three M2 anemometers are shown in table 1 together with height derived in the exact same manner from RANS calculations. The difference are negligible.



**Figure 1.** Forest edge experiment with sonic anemometer positions indicated by red dots on the two masts M1 upstream and M2 downstream of the edge. The approximate extent of the canopy is shown as the green area. Streamlines derived from cfd going through the three top anemometers on M2 are shown.

**Table 1.** Heights of the the three topmost sonic anemometers on M2 and the corresponding heights on M1 crossing the same streamline.

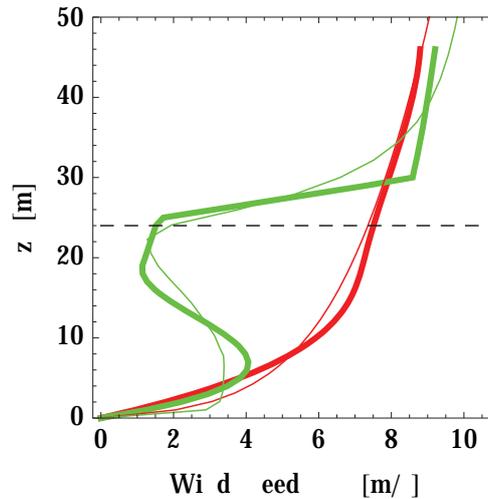
Instrument height at M2 [m]	45.9	36.9	29.9
Height of streamline at M1 [m]	35.8	25.6	17.3
Height at M1 from RANS [m]	35.7	25.1	17.4

### 2.3. Turbulence statistics

The basic second order turbulence statistics are shown in figure 3. All quantities shown are in the streamline coordinate system. For better comparison the measurements on mast M2 are shown at the height on M1 where the streamline through that anemometer is intersecting M1, and all second order statistics have been normalized with  $U_{\text{ref}}^2$ , the square of the speed at  $z = 30$  m in M1.

The plots show a marginal decrease of  $\sigma_u^2/U_{\text{ref}}^2$  over the canopy compared to the upstream values, but  $\sigma_u^2$  increases slowly towards the canopy, except the last point right above the canopy where the turbulence level is much higher due to disturbances forming over the trees. In the canopy the fluctuations almost vanish with the mean winds (see also figure 2). For  $v$  over the canopy the fluctuations are clearly enhanced, while for  $w$  they are almost unchanged but slightly reduced at the third anemometer from the top, while the lowest height over the canopy (fourth anemometer from the top)  $\sigma_w^2$  is increased. The most noticeable change is the large drop in  $-\langle uw \rangle$  towards the top of the canopy, except the last height where it is increased drastically. This difference between the three top anemometers on M2 and the fourth right over the canopy becomes more clear when we look at the spectra.

A selection of spectra from M2 is shown in figure 4. The spectra at  $z = 24$  m on M2 show much stronger fluctuations at high frequency than the three other anemometers above the canopy and the fluctuations are highly anisotropic with strongest fluctuations in  $u$ , then in  $w$  and weakest in  $v$ . The tendency of reduced  $w$ -spectrum and  $uw$ -co-spectrum above the canopy at  $z = 29$  m can also be observed. Obviously, the measurements at  $z = 29$  m, which is five meters above the canopy, are almost unaffected by the strong turbulence seen in the lower layer where low speed fluid from the canopy and high speed fluid from the approach flow are mixing.



**Figure 2.** RANS and measured mean wind speed profiles. Red: Field (M1), Green: Forest (M2). Thin lines: RANS calculation by SCADIS (Sogachev and Panferov, 2006). Thick lines: Measurements are shown smoothly interpolated. Dashed line: Approximate height of canopy.

### 3. Theory

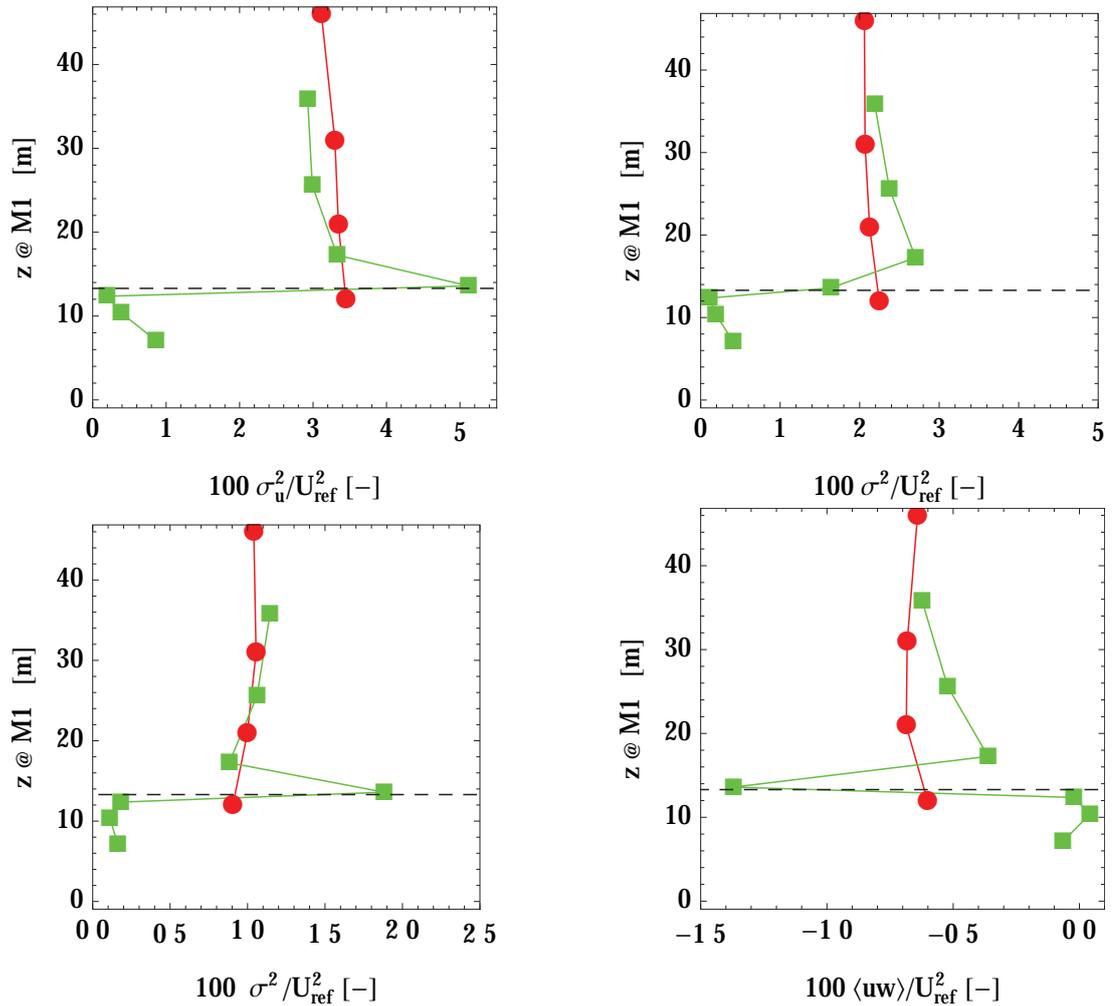
#### 3.1. Homogeneous rapid distortion theory

Rapid distortion theory (RDT) could potentially explain the reduced momentum flux, the increased transverse variance and the decreased vertical variance in the speedup zone about  $0.2h_c$  above the forest at M2. In this zone the increased roughness of the trees does not cause increased turbulence levels due to upward transport of turbulent kinetic energy. The flow above the mixing zone, which engulfs the three topmost anemometers on M2 (see figure 1) may be considered to react inviscidly to the edge, which is a central assumption of RDT. However, the application of RDT with the commonly applied assumption of a homogeneous mean flow (Townsend, 1976; Lee, 1989) neither results in a reduction of the momentum fluxes nor in the observed redistribution of TKE as shown in figure 3. In Britter et al. (1981) the change in turbulence over a two-dimensional ridge is modeled by applying RDT to isotropic turbulence (see also Batchelor and Proudman, 1954). In that work the only components of the tensor  $\partial U_i/\partial x_j$  that are taken into account are  $\partial U/\partial x$  and  $\partial W/\partial z$  with zero sum due to incompressibility, i.e. no shear in the mean flow. The results can be expressed in terms of the relative speed-up  $\Delta U/U$

$$\begin{aligned}
 \frac{\Delta \sigma_u^2}{\sigma_u^2} &= -\frac{4}{5} \frac{\Delta U}{U} \\
 \frac{\Delta \sigma_v^2}{\sigma_v^2} &\approx 0 \\
 \frac{\Delta \sigma_w^2}{\sigma_w^2} &= +\frac{4}{5} \frac{\Delta U}{U} \\
 \Delta \langle uw \rangle &= \langle uw \rangle = 0 \quad ,
 \end{aligned} \tag{4}$$

where  $\Delta$  means the change along a stream line from before to after the distortion of the mean flow. The theory is only valid when  $\Delta U/U \ll 1$ , which seems to be fulfilled (see figure 2). Anyway, this theory is inadequate in describing the changes in the turbulence, possibly due to the fact that  $\langle uw \rangle = 0$  is assumed initially.

Slightly more realistic rapid distortion theories are also investigated with non-zero  $\partial U/\partial z$ . It

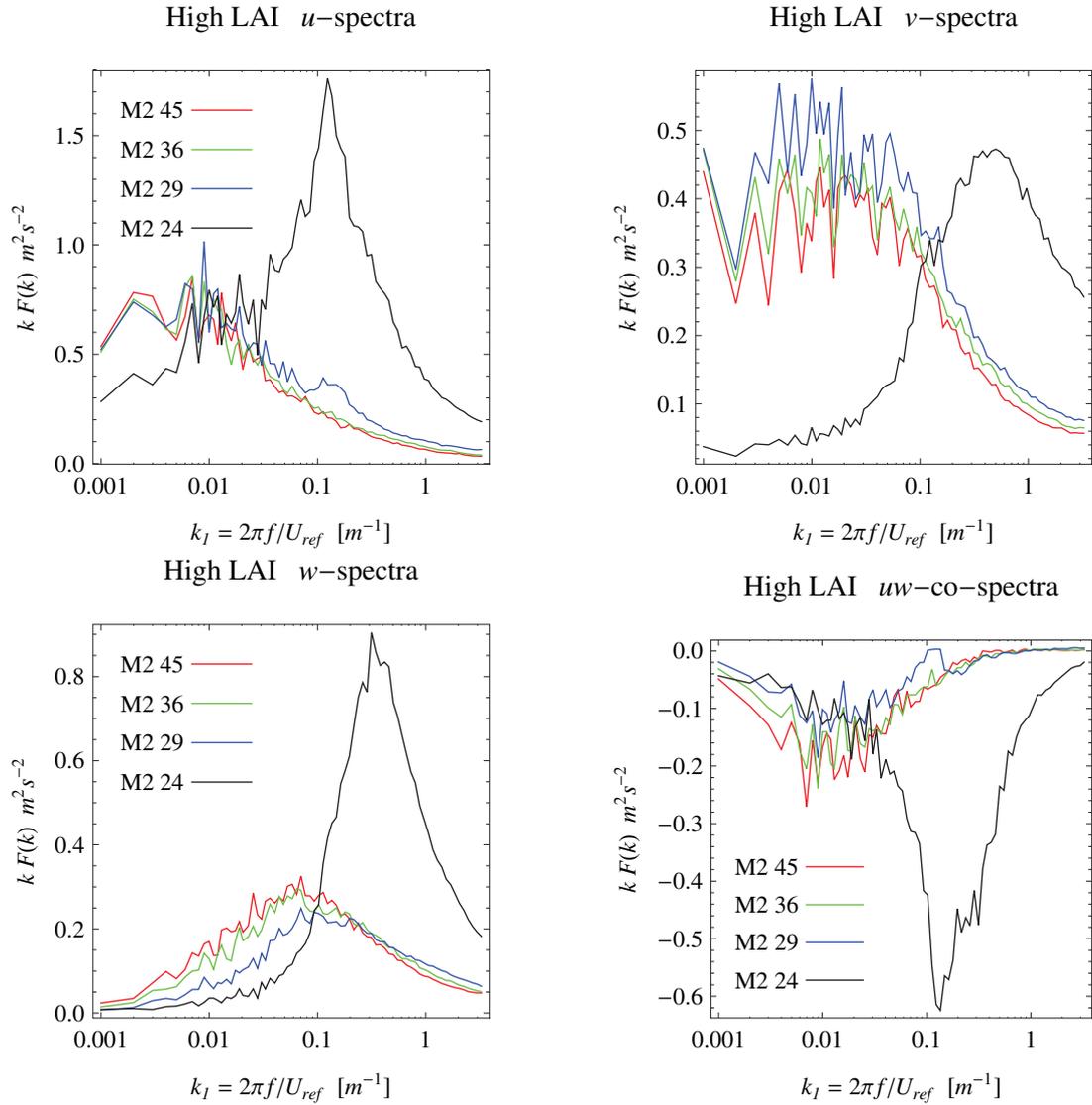


**Figure 3.** Turbulence statistics profiles at streamline heights. The data from the field mast M1 are red, the forest mast M2 green.  $U_{ref}$  is speed at 30 m at M1. The velocity components are in the streamline coordinate system. Dashed line: Approximate height of streamline at M1 that runs through the canopy top at M2.

appears that in all these theories, the momentum flux and the shear  $\partial U / \partial z$  are closely related, and because the shear is relatively unaffected by the forest edge, the momentum flux is only slightly altered. In these models it is assumed that the flow is infinite in extent, and it is probably that assumption which is violated.

### 3.2. Sudden blocking

Hunt and Graham (1978) study how isotropic turbulence is modified by the sudden introduction of a horizontal, flat plate with a slip boundary condition. The flat plate should here model the canopy top, but it is initially hard to believe that the porous canopy top could act as an impenetrable surface. However, that it indeed seems to be so can be seen from the very rapid reduction of turbulence just below the canopy top in figure 3. Moreover, there are some indications in the literature that strong shear, such as that found right at the top of the canopy, could behave as an impenetrable surface. This has been termed “shear sheltering” (Jacobs and Durbin, 1998; Hunt et al., 2013), an effect where strong shear somehow resists or blocks



**Figure 4.** Auto-spectra of the  $u$ -,  $v$ -, and  $w$ -components of the velocity and the co-spectrum of  $u$  and  $w$ . Velocity components are in the streamline coordinate system and all data are from M2 in the summer season (high leaf area index, LAI).

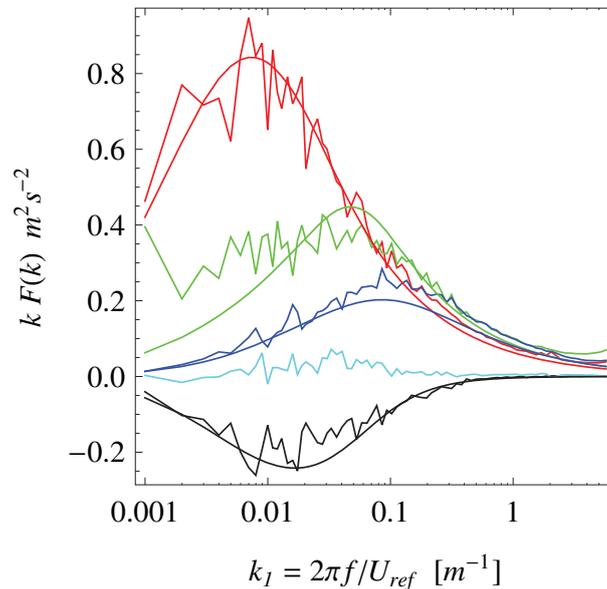
impinging eddies.

The effect of the sudden blocking on the turbulence is best described through the spectral velocity tensor (Pope, 2000) which is a function of the three-dimensional wave-vector  $\mathbf{k}$ . If  $\Phi(\mathbf{k})$  denotes the homogeneous spectral tensor before the blocking then the tensor after the sudden blocking  $\Phi^{\text{SB}}$  is not homogeneous, but depends on the distance  $z$  from the plate and the two horizontal wave-numbers. The resulting equations are

$$\Phi_{33}^{\text{SB}}(k_1, k_2, z) = \int_{-\infty}^{\infty} \Phi_{33}(\mathbf{k}) (-2e^{-\kappa z} \cos(k_3 z) + e^{-2\kappa z} + 1) dk_3, \quad (5)$$

where  $\kappa^2 = k_1^2 + k_2^2$  is the horizontal wavenumber, and for other components of the spectral

M1 20



**Figure 5.** Upstream spectra fitted to the Mann (1994) model. **u**, **v**, **w**, Co-uw, **Quad-uw**

tensor the equations become (see Hunt and Graham, 1978)

$$\Phi_{11}^{\text{SB}}(k_1, k_2, z) = \int_{-\infty}^{\infty} \Phi_{11}(\mathbf{k}) + \frac{k_1^2}{\kappa^2} e^{-2\kappa z} \Phi_{33}(\mathbf{k}) + 2 \sin(k_3 z) \frac{k_1}{\kappa} e^{-\kappa z} \Phi_{13}(\mathbf{k}) dk_3 \quad (6)$$

$$\Phi_{22}^{\text{SB}}(k_1, k_2, z) = \int_{-\infty}^{\infty} \Phi_{22}(\mathbf{k}) + \frac{k_2^2}{\kappa^2} e^{-2\kappa z} \Phi_{33}(\mathbf{k}) + 2 \sin(k_3 z) \frac{k_2}{\kappa} e^{-\kappa z} \Phi_{23}(\mathbf{k}) dk_3 \quad (7)$$

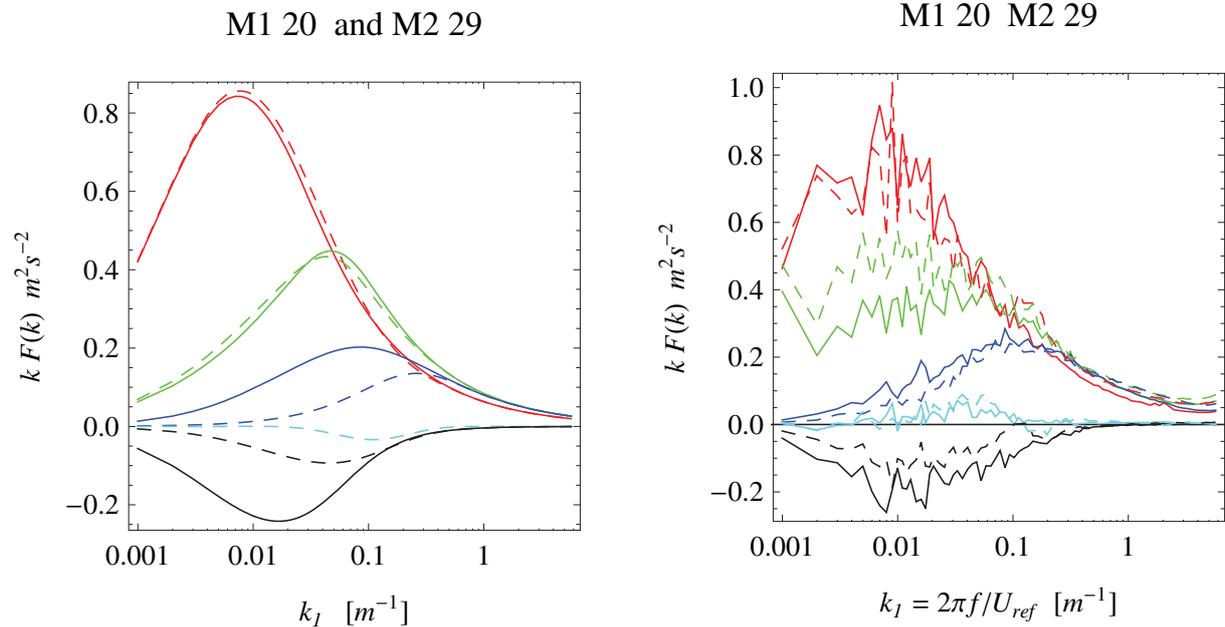
$$\Phi_{13}^{\text{SB}}(k_1, k_2, z) = \int_{-\infty}^{\infty} \left(1 - e^{-\kappa z} e^{-ik_3 z}\right) \Phi_{13}(\mathbf{k}) + i \frac{k_1}{\kappa} \left(e^{-\kappa z} - e^{ik_3 z}\right) \Phi_{33}(\mathbf{k}) dk_3 \quad (8)$$

The ordinary one-dimensional spectra are obtained by integration over all  $k_2$ . In contrast to Hunt and Graham (1978) we do not use isotropic, homogeneous turbulence as the initially unblocked turbulence, but rather the anisotropic, homogeneous tensor from Mann (1994) to fit the upstream conditions.

#### 4. Results

The Mann (1994) tensor is fitted to the upstream measurements at  $z = 20$  m at M1, see figure 5. The model parameters obtained from the fit are  $\alpha \varepsilon^{2/3} = 0.386 \text{ m}^4/3\text{s}^{-2}$ ,  $L = 24.3$  m, and  $\Gamma = 4.16$ . The length scale parameter  $L$  is higher than usual for neutral flow, and so is  $\Gamma$ , indicating that the flow might be slightly unstable despite the selection criteria (Chougule et al., 2014), or that the flow is distorted by the downwind forest edge. The model has zero quadrature spectrum between  $u$  and  $w$ , which is seen to be fulfilled. The other spectra are well fitted with the exception of the  $v$ -spectrum at low frequencies.

The equations (5) – (8) are now used to predict the turbulence at  $z = 29$  m at M2, which is close to the streamline emanating from  $z = 20$  m at M1, as shown in figure 6. It is seen that the theory predicts reduction of  $-\langle uw \rangle$  and  $\sigma_w^2$ , while the changes in the  $u$ - and  $v$ -components



**Figure 6.** Spectral comparison. Left: The upstream model spectra with the same color code as in figure 5 (solid) and the predicted spectra over the canopy (dashed). Right: Measured spectra at the same locations.

are minor. For  $-\langle uw \rangle$  and  $\sigma_w^2$  that tendency resembles the measurements, albeit the effect in reality is not so strong. One explanation could be that the approximation of the canopy top by a impenetrable, infinite plate is too simple.

## 5. Conclusion

Contrary to what one might expect the transfer of momentum towards the ground  $-\langle uw \rangle$  is reduced over a forest edge approximately one and a half canopy heights from the edge. Neither RANS nor homogeneous rapid distortion theory is capable of explaining that fact. However, inhomogeneous rapid distortion theory, or sudden blocking, does imply reduction of that flux although the predicted reduction is too strong.

## Acknowledgments

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