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TURBULENT EXCHANGE PROCESSES IN AND ABOVE TALL VEGETATION

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1. INTRODUCTION

This study presents the initial results of the complex turbulence structures observed during the experiment WALDATEM-2003 at the 'Weidenbrunnen' FLUXNET measuring site of the University of Bayreuth, Germany. This forest site is situated in the Fichtelgebirge mountains (50° 09' N, 11° 52' E, 775 m a.s.l.), with spruce (*picea abies*) as the dominant tree species and a canopy height of 19 m in the immediate vicinity of the 32 m tall main tower. The main tower was equipped with a high resolution (20 Hz) profile of sonic anemometers and vertical profiles of cup-anemometers, as well as temperature and humidity probes. CO_2 exchange was observed using CO_2 flux measurements at 33 m and 22.5 m, a vertical trace-gas and isotope profile system, and a relaxed eddy accumulation (REA) system for ^{13}C and ^{18}O isotopes. Three additional smaller towers 40 m away from the main tower measured wind speed and direction and CO_2 concentration in the sub-canopy space at 1 m and 2.25 m height. The turbulence structure in the lower atmospheric boundary layer was observed with a SODAR-RASS system located in a clearing 200 m away from the main tower. In addition, a quality assessment tool using footprint analyses was applied to identify the source areas and thus to determine how representative the measurement positions were.

2. FOOTPRINT CLIMATOLOGY OF THE SITE

To identify the footprint of the measurement data, the (Thomson, 1987) three dimensional Lagrangian stochastic trajectory model of Langevin type (e.g. Wilson and Sawford, 1996) was used. The parameterization of the flow statistics and the effect of stability on the profiles were in line with those used in Rannik et al. (2000; 2003). The model can be applied to diabatic conditions, and also considers within-canopy flow effects. Particles are dispersed by turbulent diffusion in vertical direction, along mean wind and cross mean wind directions. Furthermore, they are carried downwind by horizontal advection. In the course of this study, the simulations were performed by releasing, from a height close to the ground, $5 \cdot 10^4$ particles which were tracked until the upwind distance accounted for approximately 90 percent of the total flux. To save computation time, the flux footprint estimators were pre-calculated for a fixed set of stability classes, roughness lengths, and observation heights, and subsequently stored into tables of weighting factors.

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In order to produce maps revealing spatial structures of parameters that characterize the flow, a footprint analysis was performed for each individual measurement of the observation period. The source weight function which was obtained was projected onto a discrete matrix by assigning weighting factors ranging from zero to one to all matrix cells. The results for single measurements were collected in a database, specifying the individually assigned source weight for each matrix cell and the values of the different parameters observed. For the final evaluation of the different parameters, for each matrix cell, the footprint weighted mean value derived from all database entries was calculated. These results were visualized in two-dimensional graphs.

3. TURBULENCE STRUCTURE

The turbulence structure of the wind vector, the temperature, water vapour, and carbon dioxide concentration was studied using a wavelet tool. This tool allowed the separation of high frequency turbulence from coherent structures of lower frequencies in the terrestrial sonic data. The typical duration of coherent structures was derived from wavelet variance spectra. The individual coherent structures were detected using the zero-crossing method of the wavelet coefficients, yielding their main temporal separation (Thomas and Foken, 2004). A comparison between the wavelet variance spectra derived from the sonic data at 33 m a.g.l. and the remote sensing data obtained by the SODAR-RASS at 35 m + 45 m a.g.l. showed good agreement in the wavelet variance spectra. The detected durations of the shortest coherent structures were found to range from 18 to 25 s. The characteristic short events are missing at the higher measurement levels of the SODAR-RASS data leading to the conclusion that large-scale fluctuations seem to dominate with increasing height. The good agreement between sonic and SODAR-RASS data points is given to the fact that both techniques observe the same coherent structures.

Furthermore, the structure of turbulence was investigated using both the mixing layer analogy for exchange processes above a forest canopy according to (Raupach et al., 1996), and earlier investigations at the same site (Wichura et al., 2004).

The shear scale L_S (Equation 1) is one of the characteristic scales of a mixing layer. It depends on the wind velocity *u(h)* and the wind gradient *du/dz* at the canopy height *h* with the vorticity thickness δ_w given by

$$L_s = \delta_w / 2 = u(h) / (du/dz)_{z=h} \,. \qquad (1)$$

The second characteristic length scale is the mean separation between adjacent coherent structures Λ_x that corresponds to the wavelength of the initial Kelvin-Helmholtz instability of a mixing layer (Finnigan, 2000). Λ_x can be obtained by analyzing a time series with the wavelet technique (Brunet and Irvine, 2000). According to Raupach (1996), both length scales are related linearly by a factor *m* (Equation 2), even for non-neutral stratification (Brunet and Irvine, 2000), whereas *m* = 7...10 was found in several experimental studies for the mean separation of coherent structures in the vertical wind Λ_w.

$$\frac{\Lambda_x}{L_s} = m \cdot \qquad (2)$$

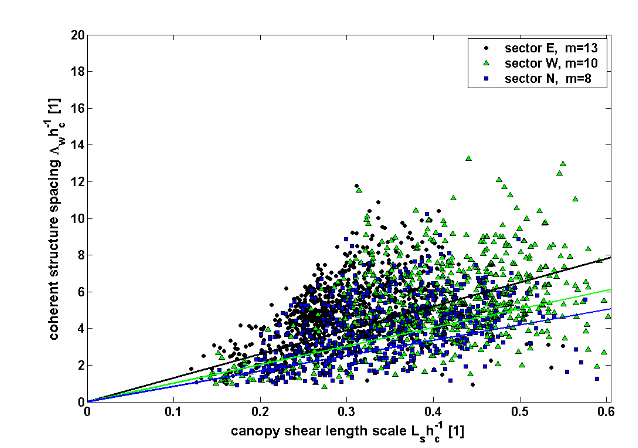

Figure 1: Coherent structure spacing Λ_w versus canopy shear length scale L_s for the main wind sectors during the WALDATEM-2003 experiment (n = 2100).

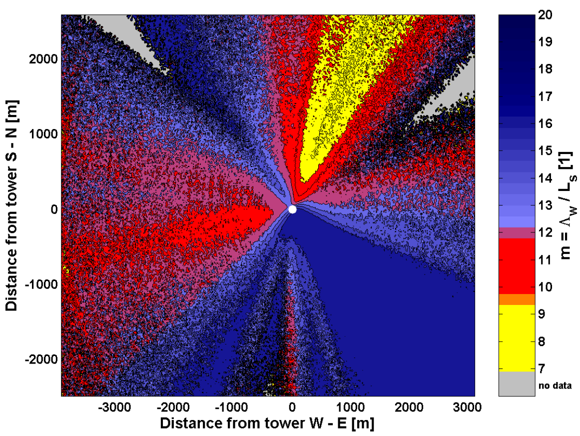

Figure 2: Footprint weighted *m* ratios (Equation 2) as a function of wind direction during the WALD-ATEM-2003 experiment. The tower position is marked with a white point.

Figure 1 plots Λ_w as a function of L_s for the entire WALDATEM-2003 experiment for the three predominant sectors of the wind direction. Data collected during the transition periods in the morning and the afternoon were rejected due to failure of the wavelet detection method. As one can clearly see, the slope *m* of the linear regression line for the different sectors ranges from ~ 8 for the North sector (320° – 50°) and ~ 10 for the West sector (200° – 300°) to ~ 13 for the East sector (70° – 180°).

This finding can be supported by applying the footprint analysis, introduced in Section 2, to the individual m ratios for each 30 minute period. The result is presented in Figure 2. Again, the smallest m values were determined for the North sector, whereas the largest could be found in the East sector, with the intermediate West sector being. This result leads to the conclusion that the predominant wind directions represent different flow conditions. Taking into account the surface topography, the West and North sectors represent up-hill and down-hill flow conditions, respectively, and in the East sector the flow plainly approaches the tower. Only the North sector, with m ~ 8, showed good agreement with previous studies. The following might be a possible explanation: When the wind comes from both the West and East sectors, it has already been influenced by the upwind surface properties. Thus, the coherent structures travelling with the mean flow carry this surface information. The approaching flow from the North comes over a hill and is thereby forced to reorganize as it moves down-hill to the tower, leading to a loss of the upwind surface information. Assuming that the flow conditions in the previous studies were not dominated by surface properties, as they were mostly conducted over completely flat terrain with long homogeneous fetches, but only by the canopy shear length scale Ls, the newly initialised flow from the North at the Waldstein site is expected to agree best with them.

4. CO_2- AND ^{13}C-Fluxes

An online analysis of the sonic vertical wind measurements and fast open path CO_2 data (LiCor 7500) allowed an optimal handling of the REA system with a hyperbolic deadband of H=1.0 (Bowling et al., 1999). The isotope REA system used was developed at our department and tested thoroughly at the Max-Planck Institute for Biogeochemistry in Jena, Germany. The precision of the ^{13}C flux measurements as shown in Figure 3a and ^{18}O fluxes (not shown) was estimated to range from 10% to 20%.

Selected results of CO_2 and ^{13}C isotope fluxes measured at 33 m a.g.l. for the period July, 6th, 12 h to July, 8th, 12h CET are presented in Figure 3a. During the first night, a respiratory CO_2 flux was observed. In contrast, during the second night no CO_2 flux could be detected with the Eddy Covariance technique. CO_2 mixing ratios obtained with the trace-gas profile system (Figure 3b) from above the canopy (solid line) and within the canopy (dashed line) give further indication of good coupling between the canopy and the atmosphere during the first night and a decoupled situation on the second night. Note the steep decrease in CO_2 mixing ratios during the start of photosynthesis on both mornings.

Figures 3c and 3d show the corresponding temperature profile within and above the canopy and the stability (z/L) measured at 33 m. For the first night, both plots indicate a typical near neutral condition. However, during the second night, very low temperatures in the canopy space and a strong stability (z/L up to 1, L: Obukhov length, z: height) inhibit the exchange of air. Consequently, no CO_2 fluxes could be observed. With the first sunlight (~4:30 h CET), the plants start to consume the respiratory CO_2 accumulated during the night in the canopy. Only at ~ 6:00 h CET do stable conditions rapidly decay and CO_2 concentrations within and above the canopy equilibrate due to turbulent exchange in the morning.

5. CONCLUSIONS

Exchange conditions over tall vegetation show a high variability concerning the dynamic of the mixing layer, coherent structures, recycling of trace gases in the steam area, etc. The tools used, like REA analysis for isotope fluxes and footprint and wavelet analysis, seem to be adequate for the study of these processes. The relevance of theses processes was shown in some examples. A further step must be to compare these studies with operating observation programs like FLUXNET to correct our present knowledge about the carbon cycle.

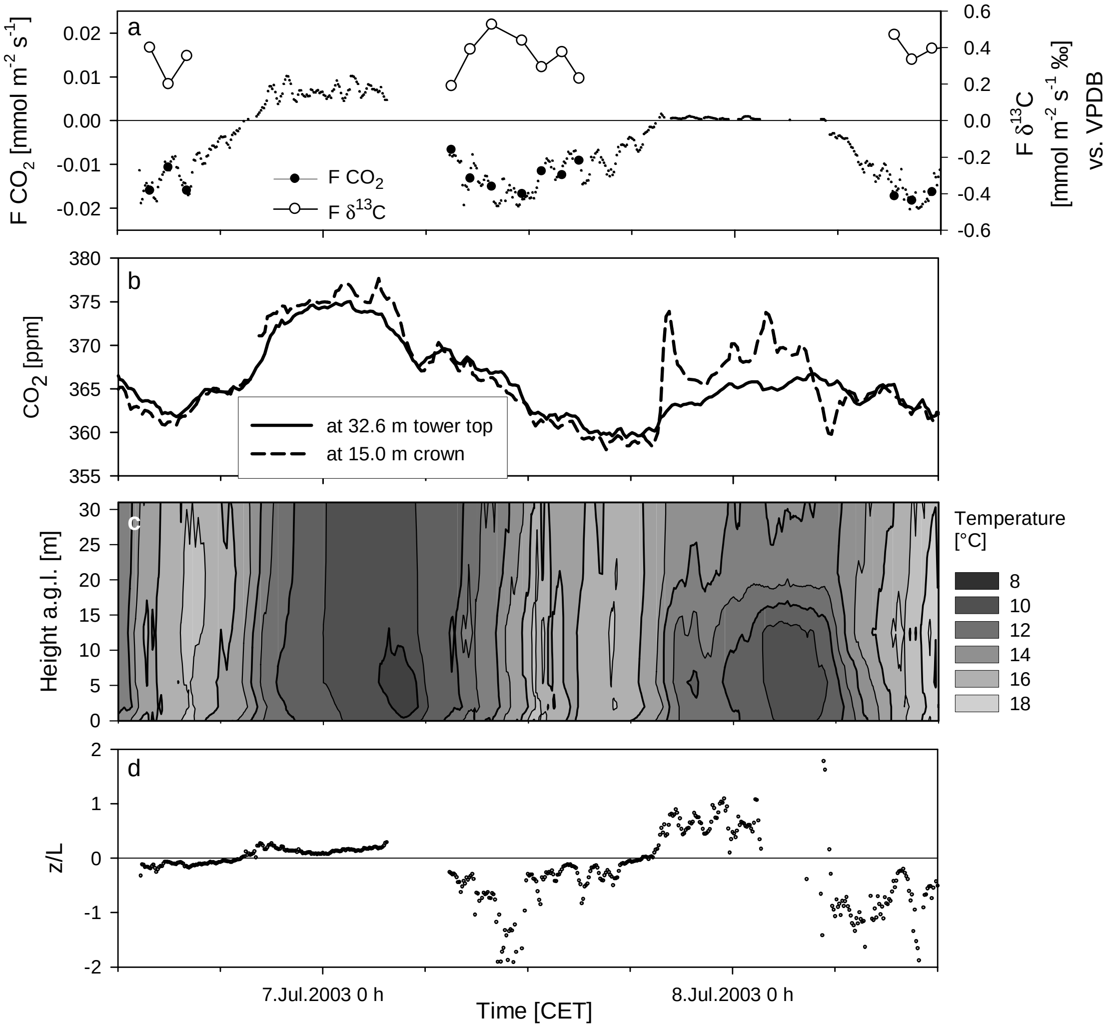

Figure 3: Selected results from the WALDATEM-2003 Experiment in and above a spruce forest (canopy height 19 m) at Waldstein Weidenbrunnen, Germany.

6. ACKNOWLEDGMENT

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