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Impact of canopy aerodynamic distance spatial and temporal variability on long term eddy covariance measurements

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ABSTRACT

Understanding if and how the spatial and temporal variability of the surrounding environment affects turbulence is essential for long-term eddy covariance measurements. It requires characterizing the surrounding environment. One way to achieve this is to analyse the canopy aerodynamic distance (Δ), which is the difference between measurement height (z_m) and displacement height (d).

In this work, an original method to estimate the canopy aerodynamic distance at a fine spatial (30° sectors) and temporal (one year) resolution was proposed. It was based on sensible heat cospectra analysis, calibrated on a measurement height change and validated using canopy height inventories.

This method was applied to 20 years of eddy covariance measurements from the Vielsalm Terrestrial Observatory (VTO), a site located in a mixed temperate forest. The method allowed Δ spatio-temporal variability due to changes in canopy or measurement height to be detected.

Relationships between Δ and turbulence statistics were then analysed: the momentum correlation coefficient (r_{uw}) was found to be dependent on Δ, confirming that the measurements were made in the roughness sublayer of the atmospheric surface layer. In contrast, no such relationship was found sensible heat, CO_2 or water vapour correlation coefficients, suggesting that the Δ variability did not affect significantly these fluxes. There were significant differences, however, between azimuthal directions, suggesting that these scalars were affected by forest heterogeneity in a different way. Various hypotheses were put forward to explain the differences and their relevance was evaluated.

This study highlighted the need to consider the spatial and temporal variability of the surrounding environment in order to verify the consistency of long-term eddy covariance datasets.

1. Introduction

The consistency of long-term (several years) temporal series is an important issue in environmental science (Irving et al., 2006), from local human surveys to global satellite data (Tian et al., 2015). Instrument consistency can often be ensured routinely by calibration, but, at the opposite, changes in the surrounding environment require identifying if and how the measurement quality (validity and representativeness) is affected and this may be more or less difficult according to the duration and intensity of those changes.

Eddy covariance (EC) systems set up for long-term measurements generally try to avoid the impact of these changes by choosing spatially (composition and structure) and temporally (growth limited and undisturbed) homogeneous ecosystems. It would also be preferable if the EC instruments were placed above the known roughness sublayer of a mature ecosystem (about twice the canopy height), where fluxes are undisturbed by roughness elements (Munger et al., 2012). In practice, however, because of natural variability and logistical limitations (e.g., tower height or limited fetch), measurements are often made in environments that do not reflect this ideal situation (Baldocchi, 2003; Moraes et al., 2008) and sometimes require taking the non-ideal conditions into account. Many studies have focused on coping with measurement representativeness issues, such as mixed composition (Aubinet et al., 2002; Aubinet et al., 2005; Morin et al., 2014) or limited fetch (Nagy et al., 2006), generally by using footprint models. There have been a few studies on the impact of canopy structure evolution on EC measurements (Zitouna-Chebbi et al., 2015; Wilkinson et al., 2016), including studies based on long-term turbulent flux time series and using turbulence statistics (Turnipseed et al., 2003; Mammarella et al., 2008). As long-term EC datasets increase in length, structural changes

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in the surrounding environment become more likely, especially in forests, from rapid and intense change (e.g., storms, harvest, tower change) to slow and gentle change (e.g., vegetation growth). Where measurements are made in the roughness sublayer of the atmospheric surface layer, these changes can affect the turbulent transport of momentum, heat and scalars, including carbon dioxide, thus potentially inducing a bias in the measured net ecosystem exchange, which could hamper the study of long-term trends in the net ecosystem exchange.

In order to study the impact of ecosystem structure heterogeneity on turbulence, it is necessary to characterise the surrounding environment. Canopy aerodynamic distance (Δ), defined as the difference between measurement height (z_m) and displacement height (d) is a key variable for such analysis.

The Δ parameter is indeed widely used in (micro-)meteorological modelling applications (e.g., in footprint models). According to Monin-Obukhov Similarity Theory (MOST), in specific stability conditions, some normalized turbulence statistics, such as similarity ratios and correlation coefficients between the wind vertical velocity and horizontal velocity or scalars should be independent of Δ if measurements are taken in the inertial sublayer while, in the roughness sublayer, an impact of Δ on turbulence statistics and fluxes is expected (Kaimal and Finnigan, 1994). Therefore, testing a possible inter-dependence between turbulence statistics and Δ can reveal the extent to which measured fluxes are influenced by structural changes in the ecosystem. This inter-dependence has been observed in turbulent flux vertical profile studies (e.g., Brunet et al., 1994), but these studies require additional inter-calibrated EC systems, making them difficult and expensive to install and maintain in the field over the long term. They are therefore impractical for studying the impact of structural changes that can be observed *in situ* at long-term monitoring stations.

Δ has however to be determined at a fine spatial and temporal resolution, especially in heterogeneous terrains or in presence of growing vegetation. Various methods have been developed to this aim, including methods based on single point EC measurements (e.g., based on similarity relationships or on wind speed relationship to stability). A comparison achieved by Graf et al. (2014) showed that these methods could provide divergent results, potentially due to the different data used by each method (Graf et al., 2014).

In this paper we propose an alternative method based on cospectral analysis.

Measurements made since 1996 at the Vielsalm Terrestrial Observatory (VTO), an ICOS (Integrated Carbon Observation System) candidate site located in a mixed temperate forest in eastern Belgium, are used to address the following key questions:

- Can defensible estimates of canopy aerodynamic distance (Δ) be obtained based on single point EC measurements?
- Can momentum, sensible heat, CO_2 and water vapour correlation coefficient variability be explained by changes in canopy aerodynamic distance (Δ)?

2. Material and methods

2.1. Site description

The VTO is located in a mature mixed forest in the Ardenne region in eastern Belgium (50°18′ N, 6°00′ E) at an altitude of about 470 m a.s.l. The forest is at least 80 years old and the 2 ha circle around the tower is composed mainly of beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* (L.) Karst.), silver fir (*Abies alba* Miller) and Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco). Canopy height evolution at the VTO will be presented in the results, but is already summarized here (Fig. 1). Thinning was done at the beginning of 2001, in mid-2003 and at the end of 2004. The soil at the site is 50–100 cm deep and is classified as a dystric cambisol. The soil is slightly sloping (3%) in north-westerly direction. The climate is temperate maritime with an annual mean temperature of 7 °C and an annual precipitation of 1000 mm. The winds blow mainly from the south-west and the north-east.

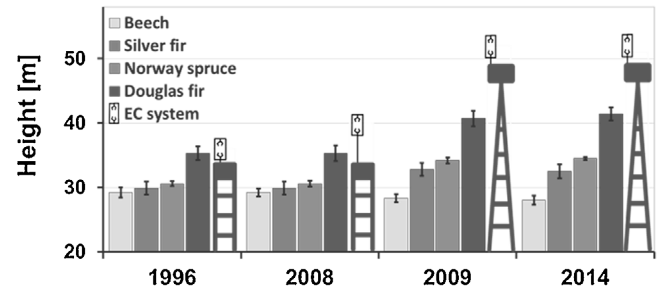

Fig. 1. Tree and sensor heights evolution between 1996 and 2014 at the Vieslalm Terrestrial Observatory. Tree heights were measured within a 200 × 60 m^2 rectangle around the tower, orientated west-east.

2.2. Site instrumentation

EC measurements have been performed at the site since 1996. The system is composed of an infrared gas analyser (LI-6262, LI-COR Inc, Lincoln, NE, USA) and a 3D sonic anemometer (SOLENT 1012R2, Gill Instruments, Lymington, UK). In 1996, the sonic anemometer sensing volume was placed at 36 m a.g.l. At the beginning of 1997, it was moved 4 m higher and, finally, in May 2009, it was installed at 52 m a.g.l in order to increase the distance between the EC system and the canopy, particularly with regard to the Douglas-firs. Canopy and sensor height evolution is schematically described in Fig. 1. The Eddysoft software package (Kolle and Rebmann, 2009) was used to perform data acquisition and flux computation for all the years. Computation and correction followed the recommended standard procedures (Rebmann et al., 2005). The double rotation method was used for coordinate rotation. The first steps of classical quality control were applied to the raw data (spike detection and stationarity test) and only those data meeting the quality criteria were retained (Aubinet et al., 1999). There is a more detailed site instrumentation description in Aubinet et al. (2001).

2.3. Canopy aerodynamic distance estimation

The canopy aerodynamic distance was deduced for each year and each 30° azimuthal direction sector by minimizing the squared difference between observed normalized sensible heat cospectra and a modelled cospectrum.

Observed sensible heat cospectra were computed (4096 points equidistant from $10^{-2.8}$ to 10^{1}) for every half-hour using a fast Fourier transform algorithm $\overline{w'T'}$(Kolle and Rebmann, 2009) and normalized by division by

Only cospectra obtained during the full vegetation period, defined as the period between May and October (when the leaves were present as the leaf area is known to impact roughness parameters (Maurer et al., 2013)) and good convection conditions (wind speed between 1 and 4 m s^{-1}, sensible heat higher than 200 Wm^{-2}, the maximal sensible heat flux observed at the site being around 700 W/m^2) were taken into account. In order to get rid of wind speed dependence, they were then transposed from the natural frequency domain (f) to a wave number domain ($k = f/u$), by division by the mean horizontal wind speed of the corresponding half-hour. After this, by 30° azimuthal direction sector and by year, the median cospectral densities for 200 wave numbers classes equidistant on a logarithmic scale between $10^{-2.9}$ and 10^{2} were computed.

Modelled cospectrum was derived from Kaimal's equation (Kaimal et al., 1972):

$$\frac{fCo_{wT}(f)}{\overline{w'T'}} = \frac{kuCo_{wT}(ku)}{\overline{w'T'}} = \frac{\alpha n}{(1 + \beta n)^{\gamma}}, \quad (1)$$