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The dependence of the β coefficient of REA system with dynamic deadband on atmospheric conditions

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This paper presents the effect of deadband width and atmospheric stability on the numerical value of empirical β coefficient related to REA system with dynamic deadband.

Abstract

We simulated the REA system with dynamic deadband to study numerical value and the effect of atmospheric conditions on the empirical constant β which relates vertical flux to concentration difference between updrafts and downdrafts. We found that the value of β depends only weakly on the friction velocity and atmospheric stability. In agreement with previous studies, the median value obtained for a system with dynamic deadband proportional to 0.5 times the running mean of the standard deviation of vertical wind speed was $\beta = 0.42 \pm 0.03$. For a single half-hour measurement one has to consider the large uncertainty of ± 0.2. According to our study, the dynamic deadband enables the use of a constant value of β in flux calculation.

Keywords: Relaxed eddy accumulation; Beta coefficient; Stability; Flux measurement

1. Introduction

The most direct method for measurements of vertical turbulent fluxes of atmospheric constituents in the atmospheric boundary layer is the eddy covariance (EC) method. In this method the flux (F_c) is calculated directly as a covariance between the vertical wind velocity (w) and concentration of the constituent (c):

$$F_c = \overline{c'w'} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} (c(t) - \overline{c})(w(t) - \overline{w})\mathrm{d}t \qquad (1)$$

where overbars denote time averages. By convention, the heat and scalar fluxes are defined to be positive upwards. As a significant portion of the vertical flux in the atmospheric boundary layer is carried by eddies with time scales less than 1 s, the measurements of w and c should be carried out with instruments with response times less than that.

To overcome the requirement of fast response analyzer, an eddy accumulation (EA) method has been proposed (Desjardins, 1977). In the EA method air is collected into two reservoirs depending on the sign of the vertical wind velocity: one reservoir for updrafts (air is collected when $w > 0$) and another for downdrafts (air sampled when $w < 0$). The true EA method requires the sampling rate into the reservoir to be proportional to the magnitude of the vertical wind speed. When this is the case, the equation for the true EA can be mathematically derived from Eq. (1). The requirement of the proportionality between the w and sampling flow has hindered the use of the true EA method, as it is hard to control the sample flow with sufficient accuracy and speed.

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To overcome the requirement of fast flow control, Businger and Oncley (1990) suggested relaxation of the proportionality requirement of the EA method. The relaxed eddy accumulation (REA) method is largely similar to the true EA method, with the exception of the constant sample flow rate. This alteration has made the REA a popular method for measurements of exchange of trace constituents between surface and the atmosphere (Guenther et al., 1996; Baker et al., 1999; Christensen et al., 2000; Gaman et al., 2004; Skov et al., 2006).

The constancy of the sample flow rate introduces an empirical constant (β) into the flux equation:

$$F_c = \sigma_w \beta \left(c^{\uparrow} - c^{\downarrow}\right) \tag{2}$$

where σ_w is the standard deviation of vertical wind speed and $c^{\uparrow}$ is mean concentration of c in reservoir for updrafts over the time period sampled. Similarly, $c^{\downarrow}$ is mean concentration of c in reservoir for downdrafts.

To increase the concentration difference and to reduce the wear of sampling valves, a deadband around $w = 0$, in which air is not sampled, was introduced into the method. The value of β depends on the deadband width, which can be decided in several ways. Generally, one makes the deadband width proportional to the σ_w. However, when an REA system is operating it does not have advance knowledge on the σ_w over the coming measurement period. One option is to use the σ_w of the past averaging period and to determine the required β value during post-processing of the data. Another option is to apply a dynamic deadband with value proportional to the running mean of σ_w (Christensen et al., 2000; Olofsson et al., 2003, 2005; Gaman et al., 2004; Haapanala et al., 2006; Grönholm et al., 2007).

In REA, the trace gas flux is calculated using parameterization based on flux-variance similarity and scalar similarity, i.e. similarity in the turbulent transport of the scalars (Ruppert et al., 2006). However, these assumptions are not necessarily valid over heterogeneous surfaces, especially in roughness sub-layer above tall vegetation (Kaimal and Finnigan, 2004; Ruppert et al., 2006).

The value of β has been studied intensively. Theoretical work has been carried out by e.g. Milne et al. (1999, 2001). They simulated REA measurements with different distributions of turbulence. However, they did not use dynamic deadband and therefore β was highly dependent on the atmospheric conditions.

In this study we obtained numerical value and uncertainty of β using wind speed, temperature and CO_2 measurements conducted at the rate of 10 Hz. Analysis is based on flux calculations using EC principle and REA simulations with dynamic deadband approach. In addition, by using the same data set we studied the influence of averaging time window on β and its applicability to flux calculation of another scalar.

2. Materials and methods

The β coefficient used in the REA method can be obtained using the fast response wind and concentration (or temperature) measurement data. This can be done for each averaging period of turbulent fluxes by inverting Eq. (2) to yield:

$$\beta = \frac{\overline{w'c'}}{\sigma_w\left(c^{\uparrow} - c^{\downarrow}\right)} \tag{3}$$

Alternatively, the mean coefficient can be determined as a slope of the dependence of $\overline{w'c'}$ on $\sigma_w(c^{\uparrow} - c^{\downarrow})$.

The data used for simulations were recorded at SMEAR II station (Station for Measuring Forest Ecosystem–Atmosphere Relationships), Hyytiälä, Southern Finland (61°51′N, 24°17′E, 181 m ASL) from February 15th to October 22nd, 2002. The measurement tower is surrounded by a Scots pine forest with dominant tree height of 14 m at that time. The roughness length for momentum of the site is about 1 m. Rannik et al. (2003) observed that at 22 m measurement level, which we used in this study, the effects of the roughness sub-layer on turbulence statistics are negligible and the vertical fluxes are constant with height. Therefore, the results obtained in this study should be applicable also to REA measurements over aerodynamically smoother surfaces. Rannik (1998) and Launiainen et al. (in press) give a comprehensive description of the turbulence characteristics at the SMEAR II site while Hari and Kulmala (2005) describe the site in more detail.

The EC system consisted of a Solent HS1199 Research ultrasonic anemometer (Gill Instruments Ltd., UK) and of an LI-6262 closed-path infrared gas analyzer (LI-COR Inc., USA) for CO_2 and water vapor concentration measurements. The response time of the LICOR-6262 gas analyzer to a step change in concentration was 0.1 s. The analog output signals from the gas analyzer were connected to the analog inputs of the anemometer for synchronization.

First, we corrected time lags between the sensors by shifting CO_2 signal according to maximum cross-correlation between the w and concentration. Also, we performed a three-dimensional coordinate rotation of wind vector to the local streamlines according to Kaimal and Finnigan (2004). After this we calculated the covariances of the w and temperature as well as w and CO_2 concentration for each 30 min averaging period. Hereafter, we call these covariances as EC fluxes. Then, using the same data set, we simulated the REA measurements with dynamic deadband approach.

In our REA simulations, we used 5-min running mean to determine the sampling threshold $\pm 0.5\sigma_w$. Based on this deadband and rotated vertical wind speed, it was determined whether the virtual REA was sampling to updraft or downdraft reservoir during each 0.1 s measurement (Fig. 1). Depending on the decision, the concentration in the virtual reservoirs was updated. After each 30-min period the average concentrations in the reservoirs were

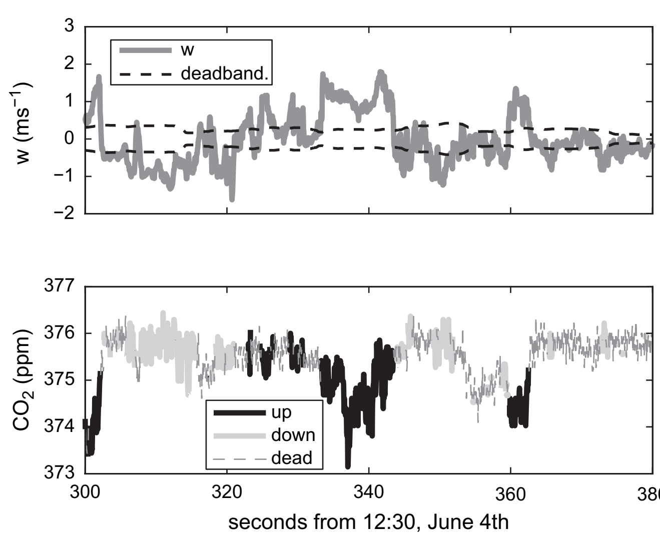

Fig. 1. An example of data used in this study: measured vertical wind speed (w) with the dynamic deadband thresholds and CO_2 concentration with the periods when air was sampled into updraft (thick black line) or downdraft (thick gray line) reservoir according to REA principles.