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Chamber techniques versus eddy covariance method during nighttime measurements

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Abstract Eddy-covariance is a very useful method for measuring ecosystem CO_2 fluxes. Its main advantages are no impact on any of the studied objects and homogenized information for desired level (predominantly ecosystem level). Nevertheless, there is a major problem in using of measured data: difficult identification and quantification of advection occurrence. The advection can underestimate or in some cases overestimate especially the night time fluxes. Chamber technique senses entire CO_2 efflux, but it is impacted by chamber effects: crypt-climate and changing CO_2 concentration. Chamber technique allows measure individual ecosystem components of CO_2 fluxes but a very high number of measured points are needed to sufficiently describe an ecosystem level.

Eddy covariance measurements were running above grassland site of the Experimental Ecological Study Site Bílý Kříž in the Beskydy Mts. (the Czech Republic). Moreover, ecosystem CO_2 efflux at the grassland site during night time periods was measured using automated chamber technique.

The results of comparison of the chamber and eddy covariance technique showed differences of measured CO_2 fluxes during night time periods. The differences between values obtained using these techniques mainly depended on net radiation and friction velocity (u*). During nights with net radiation lower than -50 W m^{-2} EC usually underestimated ecosystem CO_2 flux, during nights with net radiation higher than -50 W m^{-2} with u* lower than 0.07 m s^{-1} underestimation occurred, while u* higher than 0.07 m s^{-1} caused similar results by both methods. The chamber technique can hardly substitute eddy covariance measurements performed during nights and help to precise interpretation of eddy covariance measurements.

Key words: *Eddy covariance, Friction velocity, Chamber, Grassland, Net radiation*

Introduction

Terrestrial ecosystems, in which carbon is retained in live biomass, decomposing organic matter, and soil, play an important role in the global carbon cycle (Watson et al. 2000). Accurate measurement of CO_2 fluxes is thus necessary for a thorough understanding of carbon cycling in terrestrial ecosystems. Chamber technique (CT) and eddy covariance (EC) are two main methods used for measuring of different aspects of ecosystem carbon cycling, each with advantages and disadvantages. CT is used to characterize the spatial and temporal variability associated with the CO_2 flux in relatively small area (from cm^{-2} to m^{-2}); whereas the EC methods are used to characterize temporal variability in relatively large area (from hundreds m^{-2} to km^{-2}).

CT is subject to uncertainties associated with the so-called chamber effects (Mosier, 1990). Moreover, the spatial extent that is sampled by a chamber, or set of chambers, is relatively small compared to spatial variation of the CO_2 efflux from the ecosystem. For example, chamber artefacts and biases can cause serious error in soil respiration measurements, but can be minimized or avoided with proper chamber designs, data analyses, and spatial and temporal sampling regimes (Davidson et al., 2002). EC is a micrometeorological technique that allows a non-invasive measurement of the exchange of CO_2 between the atmosphere and several hectare area of forest, grassland or other terrestrial ecosystem (Baldocchi *et al.,* 1996, Janssens *et al*., 2001). The EC method is most accurate when the atmospheric conditions (wind, temperature, humidity, CO_2) are steady, the underlying vegetation is homogeneous and it is situated on flat terrain for an extended distance upwind. When the EC method is applied over natural and complex landscapes or during atmospheric conditions that vary with time, the quantification of CO_2 exchange between the biosphere and atmosphere must include measurements of atmospheric storage, flux divergence and advection (Baldocchi, 2003).

Even EC is a promising method, it is not certain that measurements made at night are reliable (Goulden *et al.,* 1996). Reliable measurements of flux between ecosystem and atmosphere require adequate mixing of air in the ecosystem with air above the ecosystem (Lavigne *et al*., 1997), but low wind speed and low turbulence are common at night and underestimation of the CO_2 fluxes estimated using EC method frequently occurs (Aubinet *et al,*. 2005). This underestimation could be related to friction velocity (u*). Dependence of CO_2 efflux EC measurement on u* was found (Grace et al., 1996; Goulden et al., 1996). Parametr u* is often used to distinguish between stable and well-mixed conditions (Grelle, 1997). Therefore, it is important to find the threshold value of u* to discriminate calm and windy conditions, also known as u*-correction.

Ecosystem respiration has been usually derived from daytime eddy covariance data; however, comparison with CT data, particularly during night time will improve our assessments of night fluxes. Estimation of ecosystem respiration by chamber methods works best during night time conditions, when influence of shading of solar radiation is missing, thereby air temperature difference between inside and outside the chamber is minimising. Even though, few comparisons between nocturnal EC and CT have been published (Law et al. 1999, Granier et al. 2000, Bolstad et al. 2004, Wohlfart et al. 2005) with different results, more comparisons with scaled CT measurements are needed to deeply assess the accuracy of EC measurement during the night time.

The aims of this work were i) to compare estimates of CO_2 efflux obtained by the two methods (EC, CT) at grassland ecosystem, ii) to verify reliability of night CO_2 efflux EC measurements and iii) to investigate combined influence of u* and net radiation on EC measurements.

Materials and Method

Site description

Eddy covariance and chamber measurements were carried out in a grassland at the Ecological Experimental Study Site (EESS) Bily Kriz (lat. 49°30' N, 18°32' E, 850 m a.s.l.) situated in the Moravian-Silesian Beskydy Mts., NE part of the Czech Republic. EESS Bily Kriz is characterized by a long-term mean annual temperature of 5.5°C, annual sum of precipitation of 1100-1400 mm, and mean annual relative air humidity of 80%. It is located in a mildly air-polluted region. The grassland site is situated on a mild slope (7.5°) with E orientation.

The grassland is mowed once per year, and mainly constituted of *Festuca rubra agg.* and *Nardus stricta*. Other monocotyledonous are *Avenella flexuosa*, *Carex pilulifera*, *Agrostis capillaris*. Dicotyledonous plants are represented mainly by *Veronica officinalis*, *Hieracium laevigatum*, *Potentilla erecta*. The soil is a Gleyic Luvisol according to FAO classification. Soil texture of Ah layer is loamy-sandy / loam with 15 % of gravel. Depth of the soil profile is about 80 cm. The pH/H_2O of the topsoil (6-21 cm) is 4.8. EC and CT measurements were realized during the whole growing season 2006 (May – October).

Eddy Covariance Measurements

Standard eddy covariance technique was used for measuring CO_2 fluxes comprising of ultrasonic anemometer (Solent 1012R2, Gill instruments, U.K.) installed at 1.5 m height and infrared gas analyser (Li 6262, Li-cor, U.S.A.) operating at a 21 Hz sampling rate and software for real-time (Edisol). Post-processing of the eddy covariance data is based on the methodology paper (Aubinet et al., 2000) with several modifications according to the most recent CarboEurope and FLUXNET recommendations. The Bily Kriz high frequency data was processed in a two-step procedure. First, the spike removal and quality check of the raw signals were performed by the Quality Control (QC) Software (Vickers and Mahrt, 1997). In the second step, the EdiRe software was used. Wind velocity components were rotated into the planar fit coordinate system (Wilczak et al., 2001) at the beginning of the reprocessing. Only the block time averaging of the 30 min series was applied, without signal detrending or filtering, and the turbulent fluxes of momentum, sensible heat flux, CO_2 and water vapour (latent heat) were calculated. The fluxes were then corrected for spectral loss. Final quality tests followed namely the stationarity test and the integral turbulence characteristics test (Foken and Wichura, 1996, modified). Based on these tests, quality flags (the CarboEurope scheme: 0, 1, 2) were assigned to the fluxes.

Chamber Measurements

For continuous measurements of soil and ecosystem CO_2 efflux an automatic system was developed at the Institute of Systems Biology and Ecology, Academy of Sciences of the Czech Republic. The system is called SAMTOL (it is the acronym of the Czech name). The system SAMTOL is based on automatic modified closed gasometrical (non-steady-state through-flow) system and consists of personal computer with control software, sampling multiplex, an infrared gas analyser (Li-840, Li-Cor, USA) and three big respiration chambers modified to the grass stand. The chamber (60 cm in diameter and 60 cm height,) consists of three parts, a ring inserted about 5 cm deep into the soil, tube shape wall and automatic lid. To minimize influence of change microclimatic parameters, particularly solar radiation shading, precipitation and airflow to the measured microecosystem, the tube shape wall is removed during day time and the system was operating only during night time. The system measures continuously course of soil temperature using platinum sensors PT-100 (HIT Ltd., Czech Republic) at 0.5 cm depth in side of each chamber. The big chambers allow investigating not only soil, but also whole ecosystem respiration; include aboveground biomass during night time. In SAMTOL, a chamber is closed only during gas analysis, and every other time it is left opened. The system was installed in the footprint area and periodically measured CO_2 efflux at 30 min intervals (Pavelka *et al.,* 2007).

To determine over- or under- estimation of measured CO_2 efflux, data from a period of high and low CO_2 effluxes were analysed. The change of soil plus understory CO_2 efflux rate during measurement caused by increasing CO_2 concentration in closed chambers was determined from changes of measured concentration increases. For each chamber a linear regression equation expressing change of CO_2 concentration increase was calculated. To estimate the sensitivity of CO_2 efflux to chamber effect the linear regression obtained from change of concentration increase rate was analysed. The beginning of measurement was regarded as a state with no influence on CO_2 efflux. In the used measurement schedule the decrease of soil plus above ground biomass CO_2 efflux rate during measurement caused by increasing CO_2 concentration in closed chambers showed linear trend. No statistically significant differences between underestimation of CO_2 fluxes in cases of low and high respiration activities were found (Mann-Whitney U test, alfa = 0.05). Determined decrease of CO_2 efflux values due to SAMTOL ranged from 1 to 9%. The reached accuracy is acceptable, Davidson *et al.* (2002) and Nay *et al.* (1994) reported errors of CO_2 efflux measurements carried out with closed systems in laboratory conditions range from 5 to 15%.

Supporting microclimatic measurement includes net radiation (CNR1, Kipp-Zonen, Holland), wind speed (AN1 Delta-T Devices, U.K.), temperature and humidity (RH1 Delta-T Devices, U.K.) profiles, measurement of incoming PAR (BPW 21, Telefunken, Germany), profile of soil temperature (PT 1000, HIT, CR), soil humidity (Delta-T Devices, U.K.) and precipitation (P178, Amet, CZ).

Data analysis

Night time data between 9 PM and 3 AM were taken into account. EC values with bad quality flags (= 2) were deleted and corresponding CT values were also deleted. Average value from all 3 chamber of CT was calculated for every measurement cycle (30 min). EC efflux values were normalized for temperature of soil surface 10°C (NEE_{10}) using modified Arrhénius equation [1] (Lloyd and Taylor, 1994):

$$R_{10} = \frac{R_{tot}}{\exp\left\{308.56\left(\frac{1}{56.02} - \frac{1}{T_s - 227.13}\right)\right\}} \qquad [1]$$

where R_{10} is normalized EC efflux, R_{tot} is EC measured efflux at temperature of soil surface T_s. Values of EC CO_2 efflux, friction velocity (u*), quality flags of EC measurements, CT CO_2 efflux, net radiation, wind direction, wind velocity, air and soil temperature were processed at 30 min step and averages for each observed parameter were calculated for night times. Correlations between NEE_{10} and u*, CT and u*, ratio of EC and CT CO_2 efflux measurements (EC/CT) and u* were done. Nights were divided into two groups in dependence on net radiation: nights with average net radiation lower than -50 W m^{-2}, it means with high effective net radiation of surface (HER) and nights with net radiation higher than -50 W m^{-2}, it means with low effective radiation of surface (LER). Data analysis was done using MS Excel (Microsoft, USA).

Results

Data obtained by CT were more homogeneous than EC data (Fig. 1). From data analysis a dependence of night time mean values of normalized EC flux (NEE_{10}) on u* was determined (correlation coefficient r=0.69) (Fig, 2). Dependence between CT data and u* was not found (r=0.14). Obtained data show wide scale of ratio between EC and CT (EC/CT); night time mean values obtained by EC ranged from 4% to 155% of CT values (Fig. 1). EC/CT increased with increased u* (Fig. 2). EC/CT gradually increase with u* during LER nights (Fig 4. EC/CT), while during HER nights dependence of EC/CT on u* showed more complicated shape, with rapid increasing for u* up to 0.07 and gradual increasing for u* higher than 0.07 m s^{-1} (Fig 3).

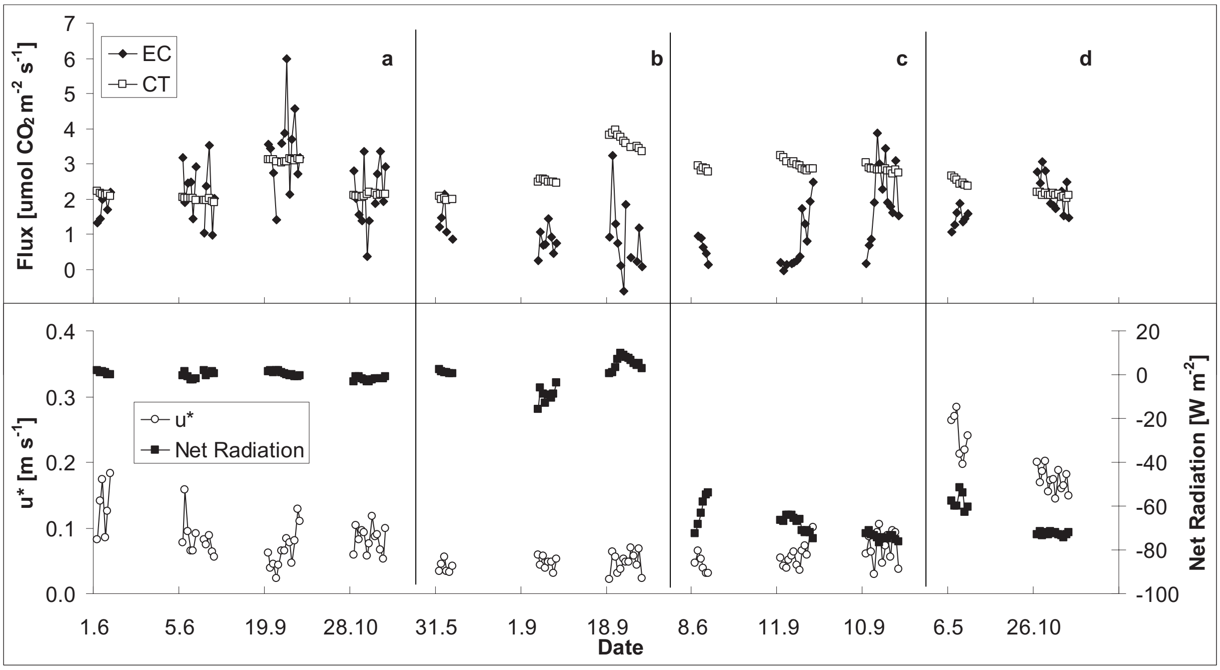

Fig. 1. Courses of CO_2 fluxes measured using eddy covariance (EC) and chamber technique (CT), friction velocity (u*) and net radiation during nights (selected typical nights during growing season 2006). Example of four types of nights: **a** – low effective radiation of surface (LER) and high u*, **b** – LER and low u*, **c** – high effective radiation of surface (HER) and low u*, **d** – HER and high u*.

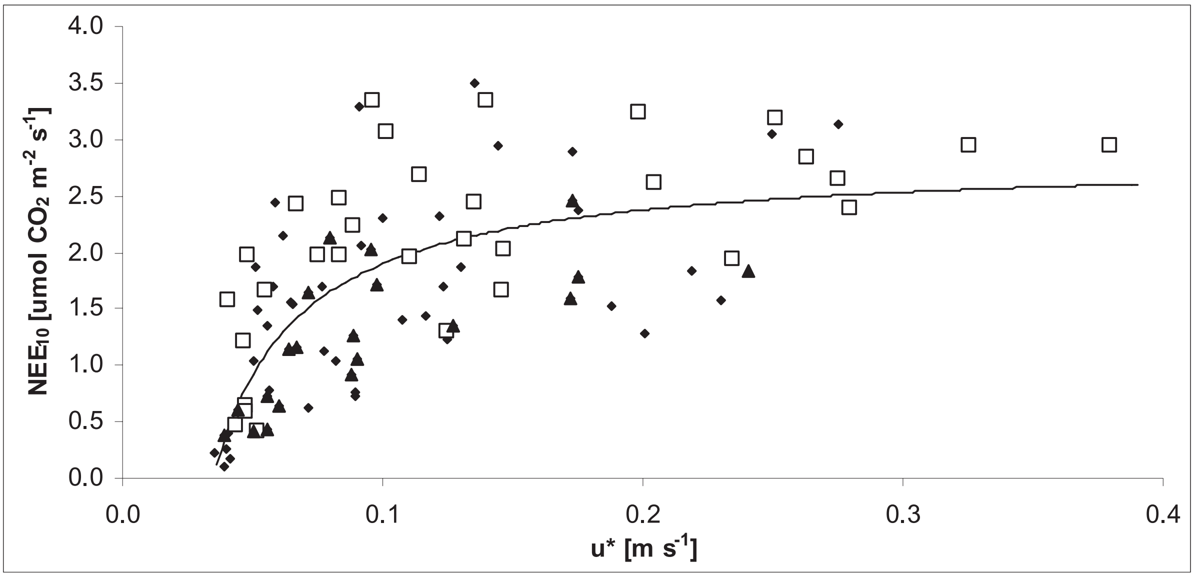

Fig. 2. Night time mean values of normalized EC flux (NEE_{10}) versus friction velocity (u*). Open squares – LER nights (net radiation >-50 W m^{-2}), closed triangles – HER nights (net radiation <-50 W m^{-2}), close dots – net radiation data missing nights. Data were fitted using hyperbolic function y = a+b/x, correlation coefficient r = 0.69.

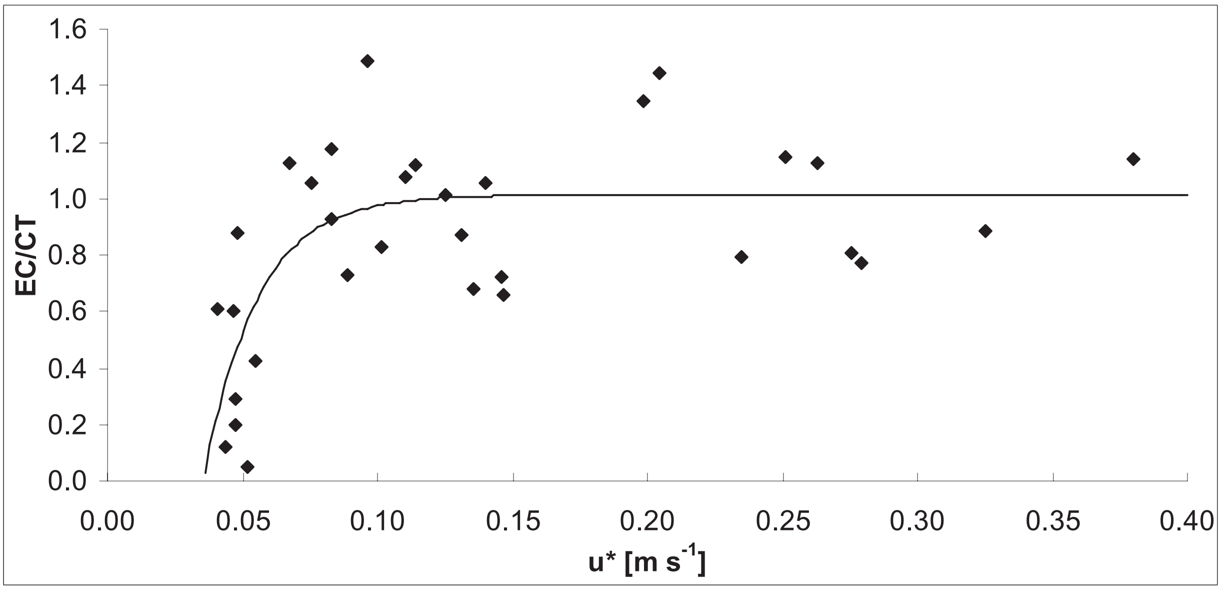

Fig. 3. Night time mean values of ratio of CO_2 efflux measured using eddy covariance and chamber technique (EC/CT) versus fiction velocity (u*) during LER nights (net radiation >-50 W m^{-2}). Data were fitted using Exponential Association function y = a(b-exp(-cx)), correlation coefficient r = 0.69.

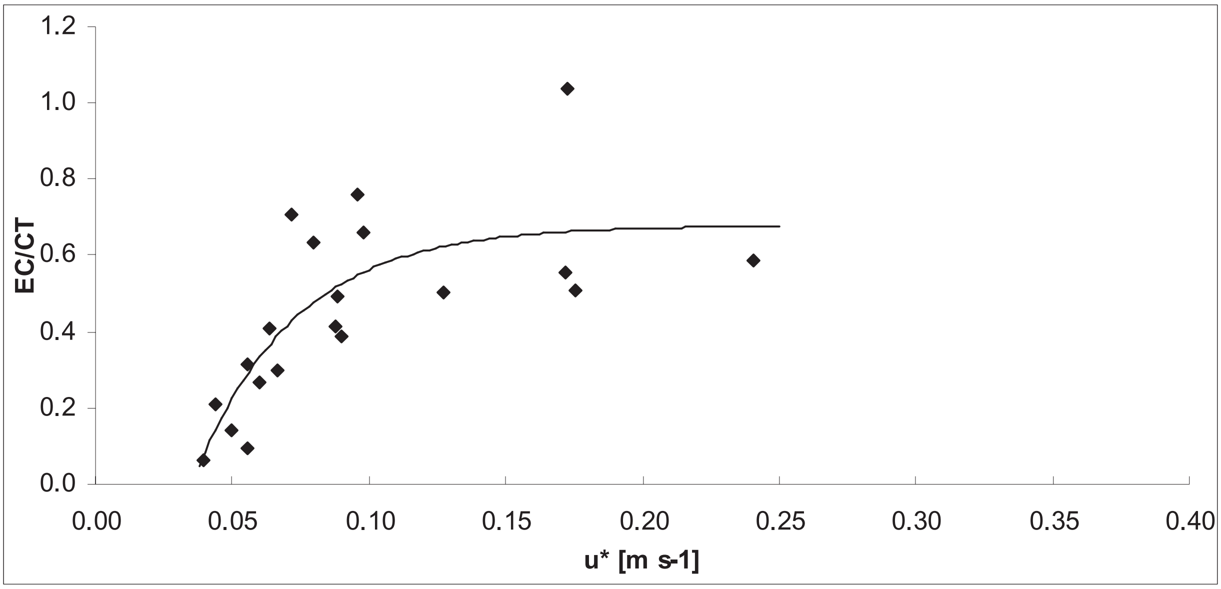

Fig. 4. Night time mean values of ratio of CO_2 efflux measured using eddy covariance and chamber technique (EC/CT) versus fiction velocity (u*) during HER nights (net radiation <-50 Wm^{-2}). Data were fitted using Exponential Association function y = a(b-exp(-cx)), correlation coefficient r = 0.75.

Discussion

From our data is evident that EC data obtained during single night are more heterogeneous than CT data (Fig. 1). The data heterogeneity was caused particularly due to periods of insufficient turbulence during night time. Respiration as a source of CO_2 for night time efflux is controlled mainly by temperature and soil water content and could not be affected by turbulence (Aubinet *et al*., 2000). Unfortunately, efflux measured using EC is influenced mainly by existence of sufficient turbulence. Our comparison of efflux measured by EC and CT showed underestimation of EC measurements, particularly for u* lower than 0.1 m s^{-1}, but the threshold value for u* correction was not clear. Therefore, net radiation as another possible parameter influencing EC efflux measurement was determined. Data was divided into two groups on the basis of net radiation.

Data acquired during HER nights (net radiation <-50 W m^{-2}) show underestimation of EC in all observed u* scale (Fig. 4). It could be caused by establishing of stable atmospheric stratification, which attenuated turbulence. Only 25% of HER nights produced higher EC/CT than 0.6 and only during one night the ratio was higher than 0.8. It means that during HER nights EC measurements produce underestimation of CO_2 efflux. From fitting curve we can predict, that for extremely high u* EC measurements could be without underestimation, but we found no u* values higher than 0.25 m s^{-1} during HER nights (Fig. 4). The absence of high u* was probably caused by the fact, that during HER nights stable atmospheric stratification occurs and the stratification attenuates turbulence thereby u* is low.

Data acquired during LER nights (net radiation >-50 W m^{-2}) show different shape (Fig. 3). EC/CT increased rapidly with increasing u* up to the threshold value (about 0.07 m s^{-1}), then the ratio oscillated about 1 for u* higher than 0.07 m s^{-1}. At meadow site Wohlfhahrt *at al.* (2005) found increasing of temperature normalised ecosystem respiration (R^*_{eco}) with u* up to 0.15 m s^{-1} including soft flagged data (if the deviation from the integral turbulence or stationarity test exceeded 30%). For data excluding soft flagged data R^*_{eco} increased with u* up to 0.1 m s^{-1}. Value for u* corrections were ranged from 0.15 to 0.40 m s^{-1} for forest sites and from 0.10 to 0.25 m s^{-1} for non forested sites (Falge et al., 2000). Aubinet *at al.* (2002) replaced night EC measurements obtained during periods of low turbulence when u* was lower than 0.5 m s^{-1} (forested site). EC/CT for u* > 0.07 m s^{-1} oscillated around 1 in relatively wide range (mean 1.00, standard deviation 0.23) (Fig. 3.). It indicates that EC measurements are influenced by other parameters. We tried to shrink the wide range of EC/CT, therefore we tested different parameters like data quality flags, net radiation, precipitation, day of year, but no correlation was found. From our analysis we consider that the influence of net radiation on EC measurement takes effect as a threshold.

Conclusions

Eddy covariance measurements at night were not reliable especially during nights with extremely low u*. Moreover, we found dependence of EC measurement reliability on net radiation. During HER nights EC usually underestimate ecosystem CO_2 efflux, during LER nights with u* lower than 0.07 m s^{-1} underestimation occurred, while u* higher than 0.07 m s^{-1} caused similar measurements by both methods. CT can hardly substitute EC measurements but it can be a useful tool to revise EC measurement during the inconvenient atmospheric conditions. When used together, the chamber and EC methods provide information of a complementary nature that can greatly improve our understanding of the ecosystem carbon budget.

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