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Net ecosystem CO_2 exchange measurements by the closed chamber method and the eddy covariance technique and their dependence on atmospheric conditions

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Abstract. Carbon dioxide flux measurements in ecosystem sciences are mostly conducted by eddy covariance technique or the closed chamber method. But there is a lack of detailed comparisons that assess present differences and uncertainties. To determine underlying processes, a 10-day, side-by-side measurement of the net ecosystem exchange with both techniques was evaluated with regard to various atmospheric conditions during the diurnal cycle. It was found that, depending on the particular atmospheric condition, the chamber carbon dioxide flux was either (i) equal to the carbon dioxide flux measured by the reference method eddy covariance, by day with well-developed atmospheric turbulence; (ii) higher, in the afternoon in times of oasis effect; (iii) lower, predominantly at night while large coherent structure fluxes or high wind velocities prevailed; or (iv) showed less variation in the flux pattern, at night while stable stratification was present. At night – when respiration forms the net ecosystem exchange – lower chamber carbon dioxide fluxes were found. In the afternoon – when the ecosystem is still a net carbon sink – the carbon dioxide fluxes measured by the chamber prevailed. These two complementary aspects resulted in an overestimation of the ecosystem sink capacity by the chamber of 40 % in this study.

1 Introduction

Net ecosystem exchange (NEE) of grasslands is today predominantly determined by eddy covariance (EC) technique (Moncrieff et al., 1997; Baldocchi, 2003; Foken et al., 2012a; Wohlfahrt et al., 2012) and the chamber method (Davidson et al., 2002; Subke and Tenhunen, 2004; Denmead, 2008). The chamber method also becomes relevant when measuring underlying fluxes of NEE (e.g., ecosystem respiration, R_{ECO}) directly and separately. Also gross primary production (GPP) of the biosphere can be easily determined by combining the use of dark (R_{ECO}) and transparent chambers (NEE) and simple subtraction of the resulting fluxes.

Numerous comparison experiments between different chambers (Pumpanen et al., 2004; Rochette and Hutchinson, 2005) and between chamber data and EC data (Subke and Tenhunen, 2004; Kutzbach et al., 2007; Myklebust et al., 2008; Wang et al., 2013) can be found in the literature. Comparisons between chamber and EC measurements are also available for other trace gases. For example, Werle and Kormann (2001) found that chambers may overestimate CH_4 emissions by up to 60–80 %. Differences were, for example, found due to methodological problems under high vegetation (Subke and Tenhunen, 2004), at times with low turbulence intensity (van Gorsel et al., 2007), at night over complex surfaces (Myklebust et al., 2008), due to poor regression analysis in the chamber software (Kutzbach et al., 2007)

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or different target areas (Reth et al., 2005). The EC method is, by definition, a direct measuring method (Montgomery, 1948; Obukhov, 1951; Swinbank, 1951) for determining turbulent fluxes. However, several conditions must be fulfilled before the method can be applied as a reference method. Most important in this context are steady-state conditions, flat and homogeneous terrain and turbulent exchange conditions (Lee et al., 2004; Foken, 2008; Aubinet et al., 2012). The control of these conditions is achieved by applying data quality tools (Foken and Wichura, 1996; Vickers and Mahrt, 1997; Foken et al., 2004), the application of which has recently come to represent the state of the art. In contrast to EC – which measures an integrated signal from a large flux footprint area (Rannik et al., 2012) – it is often challenging to achieve adequate representativeness with the chamber method on ecosystem scales (Reth et al., 2005; Laine et al., 2006; Denmead, 2008; Fox et al., 2008). In any case, both EC and chamber methods must be reviewed for inaccuracies (Davidson et al., 2002), and due to the fact that real fluxes are always unknown under field conditions, it is impossible to validate flux measurements by any technique (Rochette and Hutchinson, 2005).

Chamber measurement technique has improved during recent years and eliminated many chamber effects (Rochette and Hutchinson, 2005) to the point where pressure inconsistencies between inside and outside the chamber at various wind velocities can be avoided (Xu et al., 2006). But some challenges still remain; for example, inside chambers, atmospheric turbulence cannot be reproduced (Kimball and Lemon, 1971; Pumpanen et al., 2004; Rochette and Hutchinson, 2005) even when ventilators are used for mixing (Kimball and Lemon, 1972).

Atmospheric turbulence has a typical size spectrum and distribution of the turbulent eddies, depending on height and surface structure. In particular, larger, low-frequency flow patterns, i.e., coherent structures (Collineau and Brunet, 1993; Gao et al., 1989; Thomas and Foken, 2007), may cause differences between chamber and EC measurement results. Another cause of flux differences can be differing atmospheric stratification. Closed chambers completely cover the ecosystem during the measurement process and thereby alter the natural long-wave radiation balance to almost zero. This causes reduced surface cooling, weak development of stable stratification and finally higher fluxes compared to EC.

In this study it is not the differences in NEE between two measurement principles in general but rather the changing differences under varying atmospheric conditions in the course of the diurnal cycle that are investigated.

2 Material and methods

2.1 Study area

The comparison experiment was conducted from 25 May to 3 June in 2011 on an extensively managed submontane grassland site at the edge of the low mountain range Fichtelgebirge in northeast Bavaria, Germany. The site is located on flat terrain 624 m a.s.l. (50°05′25″ N, 11°51′25″ E) between Großer Waldstein (elevation: 877 m) to the north and Schneeberg (1051 m) to the south. Thus, a channeled wind field in west–east direction with west (263°) as prevailing wind direction is created at the site. Most of the data were collected under ideal weather conditions without rainfall and with sufficient global radiation. Weak data due to dewfall on the instruments and one heavy rainfall event (38.2 mm) in the night of 31 May to 1 June were excluded. The canopy height was about 20 cm. Thus, the chamber could be installed without any cutting of the vegetation.

2.2 Eddy covariance

For the determination of the CO_2 flux, the concentration was measured by an open-path gas analyzer (LI-7500, LI-COR Biosciences, Lincoln, NE, USA), and the wind vector by a 3-D sonic anemometer (CSAT3, Campbell Scientific, Inc., Logan, UT, USA) at high frequency (20 Hz), 2.5 m above ground. Data were stored on a data logger (CR3000, Campbell Scientific, Inc., Logan, UT, USA) and collected daily by a computer system as a backup. Data were post-processed and quality-controlled based on the latest micrometeorological standards by the software package TK2, developed at the University of Bayreuth (Mauder and Foken, 2004). This still evolving software (TK3 has become available in the meantime: Mauder and Foken, 2011) incorporates all necessary data correction and data quality tools (Foken et al., 2012b). It was successfully proved in comparison with six other commonly used software packages (Mauder et al., 2008). For every averaging interval of 30 min, the included quality flagging system evaluated stationarity and turbulence and marked the resulting flux with quality flags from 1 (very good quality) to 9 (very low quality) (Foken and Wichura, 1996; Foken et al., 2004). In this study only data with quality 3 or better were used. Also footprint analysis (not shown here) after Göckede et al. (2004, 2006) and Rannik et al. (2000) was performed to assure that the measured data exclusively represented the target land use type grassland, i.e., the ecosystem measured by the chamber (cf. Reth et al., 2005). Due to the channeled wind regime, two club-shaped footprints evolved in the western and eastern directions. Thus, disturbances of the turbulence measurements could be easily avoided by installing all other experimental devices close to the EC mast, but perpendicular to the main wind direction. Accompanying measurements of important micrometeorological parameters such as up- and downwelling shortwave and long-wave radiation, air and soil temperature, humidity and soil moisture and precipitation were accomplished by an automated weather station and stored as 10 min averages.

2.3 Chamber system

The applied system (LI-8100-104C, transparent for NEE measurements at low vegetation, LI-COR Biosciences, Lincoln, NE, USA) was an automated flow-through non-steady-state soil chamber, where sample air was constantly circulated between the chamber and an infrared gas analyzer (IRGA) by a rotary pump with 1.5 L min^{-1} through a chamber volume of 4822 cm^3. The CO_2 flux was estimated from the rate of CO_2 concentration change inside the chamber during a close time of 90 s. The chamber was designed to minimize perturbations to the surrounding environmental conditions. For example, the base plate was perforated to avoid heating of the surface and a concentration gradient-induced impedance of soil respiration (LI-COR, 2004). The soil collars, which included an area of 318 cm^2, were pre-installed 10 cm deep in the soil 2 weeks before the experiment to create a perfect seal and to avoid disturbances of the CO_2 efflux by cut and wounded plant roots at the beginning of the measurement period. Due to the channeled wind field on the site (see Sect. 2.1), the chamber could be installed very close to the eddy covariance mast without disturbing the flux footprint. The chamber had a lift-and-rotate drive mechanism that rotated the bowl-shaped chamber 180° away from the collar. This shape allowed good mixing by means of the circulation of the sample air through the IRGA alone, without a ventilator (LI-COR, 2004). Barometric- and – above all – turbulence-induced pressure fluctuations above the ground surface influence the efflux from the soil. Thus, modern chambers are equipped with a venting tube that transmits atmospheric pressure changes to the chamber headspace (Rochette and Hutchinson, 2005). LI-COR installed a patent-pending pressure vent with tapered cross section at the top of the chamber, which minimizes pressure pulses at chamber closing and allows the tracking of ambient pressure under calm and windy conditions by eliminating the Venturi effect (Conen and Smith, 1998) occurring at former simple open vent tubes (Xu et al., 2006). The exchange through the venting tube is negligible compared to the CO_2 diluting effect by water vapor during the measurement, which in turn is corrected by the measurement software (LI-COR, 2004). For R_{ECO} measurements a dark chamber is used that avoids CO_2 uptake by assimilation. NEE is measured by a chamber with a transparent dome that enables CO_2 uptake by assimilation as well as respiration processes inside. The transparent chamber for the NEE comparison was closed for 90 seconds four times during a half-hour period. In the meantime the system was flushed for 135 s, the dark chamber was measuring for 90 s (data were required for another study and not used in this one), and the system was flushed with ambient air again. The closing and opening process of the transparent chamber as part of the flushing time lasted 13 s each.

2.4 Typical exchange conditions

The application of the eddy covariance technique requires turbulent conditions (Foken et al., 2012a). Ecologists often evaluate this using a friction velocity threshold (Goulden et al., 1996), but more precise is a test on steady-state conditions and the fulfillment of typical similarity conditions (Foken and Wichura, 1996). At daytime in most cases, both criteria are fulfilled whereas nighttime exchange conditions are more challenging.

Already in the late afternoon, stable stratification of the near-surface air layer begins with cooling due to evaporation and the long-wave upwelling radiation outbalancing the long-wave downwelling radiation. Exchange is poor under stable conditions and, for example, the respiration causes the carbon dioxide concentration to increase in the first centimeters of the atmosphere up to a partial pressure equivalent to that in the soil, which consequently reduces the gas exchange. However, an ecosystem covered with a chamber dome is subjected to balanced outgoing and incoming long-wave radiation and therefore less cooling at that time of the day. Naturally under those conditions, the so-called oasis effect occurs, which is named after the moisture-dependent cooling effect occurring in oases and is defined as a sensible heat flux (Q_H) changing to negative values in combination with a still large positive latent heat flux (Q_E) and solar radiation (Stull, 1988; Foken, 2008). A lack of sensible heat causes reduction of buoyancy and consequently turbulence. This is directly detected by the EC technique, i.e., exactly the measurement of turbulent fluxes (Aubinet et al., 2012). In addition to the radiation effect, the reaction of the chamber system is also less pronounced due to the physical barrier to the surrounding, increasingly stable stratified air masses. With the sunset the remaining assimilation potential is gone, the difference between both systems declines, and other processes come to the fore.

Under stable stratification and low turbulence, the flux contribution of coherent structures to the entire flux increases (Collineau and Brunet, 1993; Gao et al., 1989; Thomas and Foken, 2007; Holmes et al., 2012). These well-organized structures, with typical periods of 10–100 s, are caused by strong roughness or landscape heterogeneities such as tree lines, bushes and ditches. Coherent structures in a steady state can be measured by eddy covariance technique (Desjardins, 1977). Analyzing methods for coherent structures are based on, for example, wavelet technology and were presented by Collineau and Brunet (1993), Thomas and Foken (2005) and Serafimovich et al. (2011). In the present study, we applied the method described by Thomas and Foken (2005) to determine the flux by coherent structures (F_{CS}) and its contribution to the entire flux ($F_{CS}\ F_{ent}^{-1}$).

3 Results and discussion

Scatter charts are often utilized in literature when measurement technique comparisons are discussed. However, they provide only a first impression of the overall behavior of both systems, and in this study Fig. 1 is intended as an introduction to further detailed breakdown of the behavior into underlying processes. So as not to adulterate the comparison results, data with bad quality were excluded by the quality flagging system (16 %), and no gap filling procedures were conducted. In any event, only data were used when both systems provided data of high quality. Data gaps were predominantly occurring at night, when CO_2 source fluxes (positive sign) prevailed. Thus, the resulting mean CO_2 values of −4.0 (EC) and −5.6 µmol m^{-2} s^{-1} (chamber) for the overall 10-day balance might be overestimated. Hence, at that time, both EC and chamber define the ecosystem to be a CO_2 sink, but the absolute value of the chamber sink flux was 40 % larger than that of EC. This is similar to other studies (Wang et al., 2009; Fox et al., 2008) and includes – in our case – smaller chamber CO_2 source fluxes of 26 % during the night and larger chamber CO_2 sink fluxes of 14 % during the day (negative sign). A first indication as to the cause of the large difference at night may be provided by the kind and dimension of scattering of the measured fluxes, presented in Fig. 1 as interquartile ranges. While daytime CO_2 fluxes of both techniques scatter quite similarly, with interquartile ranges of 0.0086 mmol CO_2 m^{-2} s^{-1} and 0.0094 mmol CO_2 m^{-2} s^{-1}, respectively, for positive nighttime CO_2 fluxes, much larger scattering in EC data (interquartile range: 0.0039 mmol CO_2 m^{-2} s^{-1}) than in chamber data (0.0018 mmol CO_2 m^{-2} s^{-1}) could be recognized (see Fig. 1 and cf. Janssens et al., 2001).

This kind of aggregation of the positive chamber fluxes (cf. Laine et al., 2006) had various associated reasons that are explained in the following. There must be also an explanation for the domination of the chamber in small negative CO_2 fluxes, not only when both systems showed fluxes with opposite directions (Fig. 1, light grey filled circles) but also when both were negative. To investigate underlying short-term effects on the comparability, EC–chamber flux differences – normalized with the EC flux – were calculated and illustrated as mean diurnal cycles of the whole measurement period (Fig. 2a)

The characteristics of the normalized EC–chamber flux difference suggested a classification into four different periods. The early morning transition time was affected by sunrise, developing turbulence and temporary wet instruments due to dewfall, and this prevented proper data analysis for this period. Later, during the day, when the atmospheric turbulence was well developed, the mean difference was almost zero (i.e., both systems worked well and showed similar results). In contrast, in the late afternoon, CO_2 sink fluxes within the chamber were sustained longer and were larger, resulting in a flux up to twice as large as the EC flux (Fig. 2a).

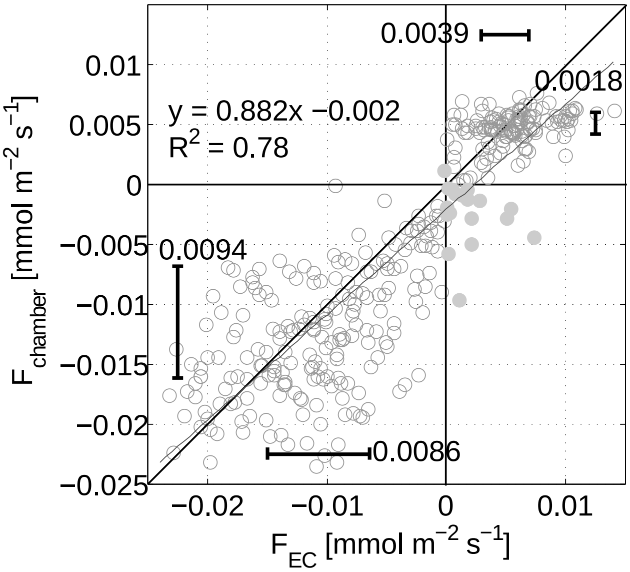

Fig. 1. Scatterplot of EC- and chamber-determined NEE: light grey filled circles represent CO_2 fluxes with opposite directions, and black bars show interquartile ranges of EC/chamber CO_2 source and sink fluxes, respectively (opposite CO_2 fluxes excluded).

The reason was defined as the oasis effect, i.e., cooling and stabilization effects outside the chamber (see Sect. 2.4). In Fig. 2b just the normalized flux differences during periods of prevailing oasis effect are considered, which precisely reproduces the late afternoon and to a small extent early afternoon chamber dominance. Nearly all measurements influenced by the oasis effect show larger chamber fluxes (Fig. 3a). Also two-thirds of the situations with contrary EC–chamber flux directions (filled circles, Figs. 1 and 3a) and the higher sink fluxes of the chamber at small values could be directly explained by the oasis effect (black circles, Fig. 3a). With the sunset this effect disappears, as does the assimilation potential of the ecosystem, and the difference between both systems declines.

After a short evening transition time, the fourth period with typical nighttime conditions arises – characterized by predominantly stable stratification (Fig. 2d) and increasing exchange by coherent structures (Fig. 2c). For mid-latitudes this is the typical diurnal cycle for stratification (Foken, 2008). Coherent structures can cause 50–100 % of the gas exchange during nighttime and 10–20 % during the day above a forest (Thomas and Foken, 2007). The influence of coherent structures might be less above meadows due to the negligible mixing layer (roughness sublayer). In contrast to daytime CO_2 fluxes that scatter quite similarly (see interquartile ranges in Fig. 1), nighttime chamber fluxes scatter less than half as much as the EC fluxes: the chamber measures a virtually constant flux during the night. As Fig. 3b, c and d illustrate, this predominantly occurs at times with high atmospheric stability, presented along with low wind velocity

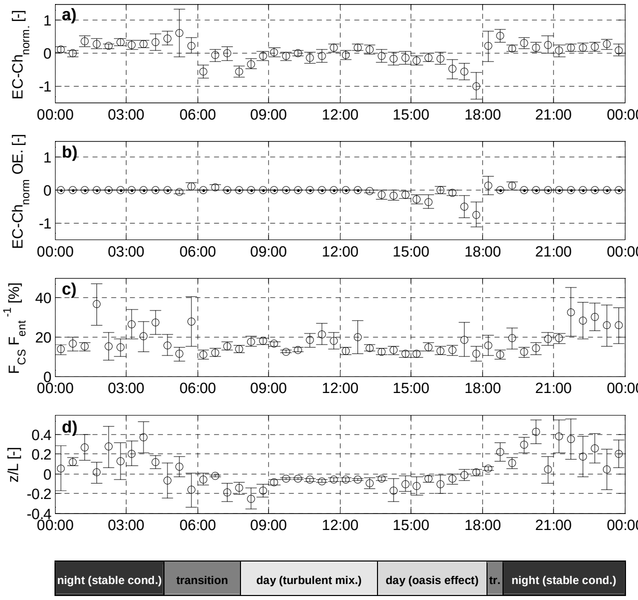

Fig. 2. Mean diurnal cycles of **(a)** normalized EC–chamber CO_2 flux differences, **(b)** normalized EC–chamber CO_2 flux differences during times with oasis effect (OE), **(c)** absolute proportion of fluxes by coherent structures and **(d)** the stratification defined by the stability parameter z/L (z: height, L: Obukhov length); the bars below indicate different regimes of atmospheric mixing during the day; incoming shortwave radiation reaches $80\,\mathrm{W\,m^{-2}}$ at 05:30 and finally at 19:00; time in CET = UTC + 1; error bars indicate variation within the 10-day period.

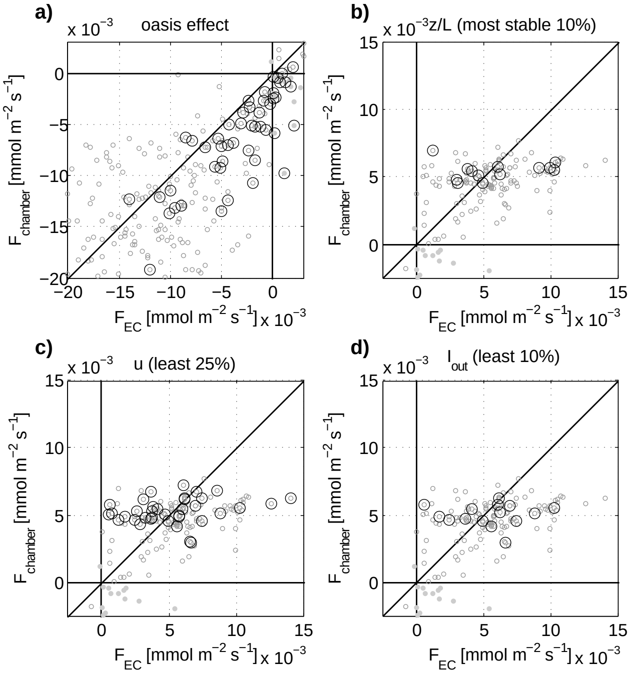

Fig. 3. Scatterplot sections of EC- and chamber-determined NEE under particular micrometeorological conditions: **(a)** oasis effect; **(b)** atmospheric stability $z/L > 0.7$; **(c)** wind velocity $u < 0.9\,\mathrm{m\,s^{-1}}$; **(d)** outgoing long-wave radiation $I_{out} < 319\,\mathrm{W\,m^{-2}}$ – labeled with large black circles in each case; light grey circles represent fluxes with different directions.

and a cool ground surface (i.e., little outgoing long-wave radiation). While the EC system responds to the smallest changes of the atmospheric conditions as well as the nighttime ecosystem respiration flux does, the chamber is directly connected to the ground surface – where the ecosystem respiration is more or less constant – with only minor influences from the surrounding atmosphere (Norman et al., 1997; Reth et al., 2005; Lai et al., 2012), transferred into the chamber system exclusively by the pressure vent (Xu et al., 2006). Besides coherent motions, which are generated by braking gravity waves or under the influence of low-level jets (Karipot et al. 2008), heating due to dewfall causes slightly higher turbulent fluxes during nighttime. The condensation heat thereby reduces the downward sensible heat flux and the strong stable stratification. Both processes are related to slightly higher wind velocities (Fig. 4b) and larger EC flux results (Fig. 1). While EC measures that wide range of CO_2 fluxes, the parameters illustrated in Fig. 3b, c and d turned out to be particularly responsible for the uniformity of the chamber flux. To clarify under which conditions the EC flux is notably larger or smaller than the chamber flux, nighttime data with higher EC fluxes were compared to those that show higher chamber fluxes. A Student's t test for dependent samples indicated no differences for the flux by coherent structures (F_{CS}), z/L and I_{out}, but did so for the wind velocity u and the friction velocity u_* (Fig. 4; u_* is not presented since the result is equivalent to u).

However, EC and chamber nighttime respiration fluxes measured at high wind velocities (largest 25 %, $u > 2.9\,\mathrm{m\,s^{-1}}$) are within the same range close to the bisecting line in Fig. 5a but with a significant tendency to larger EC fluxes. This coincides with a study of Denmead and Reicosky (2003), who found an increase of the EC flux to chamber flux ratio with the wind velocity. Although the chamber reproduces the flux variations very well at high wind velocities (i.e., it is able to describe small as well as larger fluxes), it generally underestimates the flux. Hence, at night, in addition to the stratification effect, situations with high wind velocities result in larger EC than chamber CO_2 fluxes. But these cannot really explain the highest EC fluxes in times of uniform chamber performance. It was found that some of those situations occurred together with large coherent structure fluxes (F_{CS}, Fig. 5b). In the experiment region, coherent motions were already detected as a consequence of low-level jets reaching the ground and breaking gravity waves (Foken et al., 2012c). Coherent structures appear sporadically (average in this study: $38\,\mathrm{h^{-1}}$). Thus, the total size of the coherent structure flux is less than the typical turbulent flux, yet coherent motions produce turbulence that obviously is recognized by EC but not by the chamber technique (Fig. 5b).

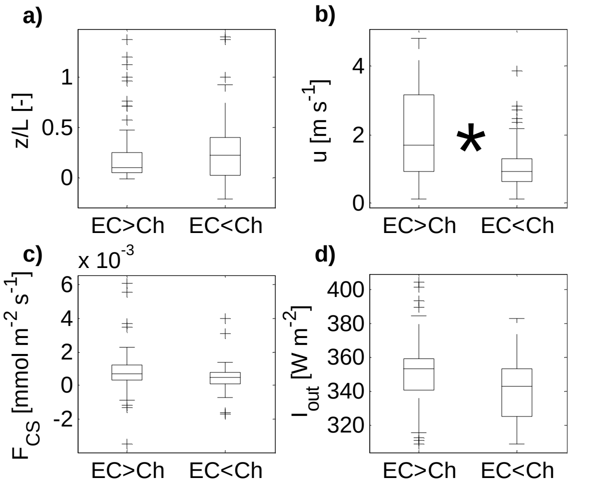

Fig. 4. Comparison of **(a)** nighttime atmospheric stability (z/L), **(b)** wind velocity (u), **(c)** CO_2 flux by coherent structures (F_{CS}) and **(d)** long-wave outgoing radiation (I_{out}) while either EC or chamber CO_2 fluxes are larger, highly significant difference (Student's t test for dependent samples, * = $p < 0.01$) found only in case of u (as well as u_*).

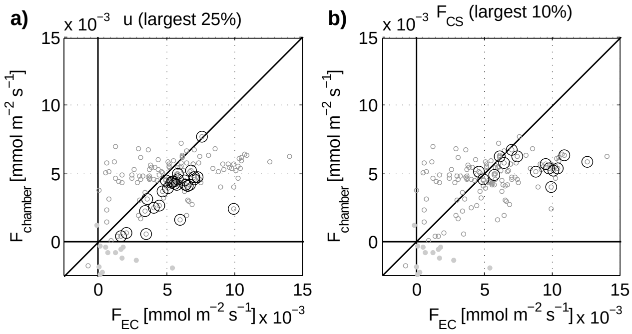

Fig. 5. Scatterplot sections of EC- and chamber-determined NEE under particular micrometeorological conditions: **(a)** largest 25 % of the wind velocities ($u > 2.9\,\mathrm{m\,s^{-1}}$); **(b)** largest 10 % of the fluxes due to coherent structures ($F_{CS} >: 0.0015\,\mathrm{mmol\,m^{-2}\,s^{-1}}$) – labeled with large black circles in each case: light grey circles represent fluxes with different directions.

4 Conclusions

Ecosystem processes are coupled to atmospheric conditions. A measurement system should be able to represent the resulting fluxes in a reasonable way. Otherwise, already small differences at small temporal scales may sum up to large errors in the estimation of the resulting flux. Because the difference between chamber and EC flux strongly depends on the diurnal variation of the atmospheric conditions, especially sporadic short-term chamber measurements as well as repeated chamber measurements at specific times of day are likely to be biased.

Chamber fluxes are larger than EC fluxes in the late afternoon due to surface cooling and development of stable stratification, which in turn reduces the turbulent exchange. During times of this oasis effect, the flux regime of the day is upheld longer in the evening within the chamber and the real atmospheric conditions are not represented.

During the night a quite uniform chamber flux and an EC flux with a much higher variability were observed. Detailed investigation of the relevant parameters revealed that the nighttime stable stratification, together with low wind velocities and low outgoing long-wave radiation, supports the uniformity of the chamber but not the EC flux. A greater variation of the chamber flux data was only found at times with high wind velocities and high friction velocities, respectively, which also resulted in a certain agreement with EC, but with overall higher EC fluxes. Hence, the chamber is less sensitive to atmospheric conditions that control the flux, because it is always less coupled to the surrounding atmosphere than EC (Lai et al., 2012; Dore et al., 2003; Reth et al., 2005).

Coherent structures were also expected to cause higher EC fluxes in general, but it was found that this was only the case with the very largest coherent structure fluxes. Those could explain a number of situations with larger EC fluxes.

Although at our experimental site EC provides satisfying results for the whole diurnal cycle – assuming that data quality regarding turbulence and stationarity is properly controlled – chamber flux measurements require accompanying assessment of at least wind velocity, radiation and temperature, to evaluate atmospheric conditions to some extent. Above all, during the night the strongest forcing parameters, global radiation and the CO_2 sink flux by assimilation are missing. Since the long-wave radiation balance is almost zero within the chamber anyway and the nighttime respiration flux from the soil is more constant than the CO_2 flux during the day, there should be nothing left to trigger variations in the chamber CO_2 flux, which do, however, occur.

The positive message is that both techniques show proper and comparable results from late morning – when all instruments have dried from dewfall – until afternoon, when the oasis effect gains more and more influence.

Chamber measurement technique has made progress in the last years, but its insensitivity to various atmospheric conditions suggests such micrometeorological tools as EC are preferable for the investigation of those processes and the determination of ecosystem fluxes.

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References

Aubinet, M., Vesala, T., and Papale, D.: Eddy Covariance, Springer, Dordrecht, Heidelberg, London, New York, 2012.

Baldocchi, D. D.: Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future, Global Change Biol., 9, 479–492, doi:10.1046/j.1365-2486.2003.00629.x, 2003.

Collineau, S. and Brunet, Y.: Detection of turbulent coherent motions in a forest canopy part I: Wavelet analysis, Bound.-Lay. Meteorol., 65, 357–379, 1993.

Conen, F. and Smith, K. A.: A re-examination of closed flux chamber methods for the measurement of trace gas emissions from soils to the atmosphere, Eur. J. Soil Sci., 49, 701–707, doi:10.1046/j.1365-2389.1998.4940701.x, 1998.

Davidson, E. A., Savage, K., Verchot, L. V., and Navarro, R.: Minimizing artefacts and biases in chamber-based measurements of soil respiration: FLUXNET 2000 Synthesis, Agr. Forest Meteorol., 113, 21–37, doi:10.1016/S0168-1923(02)00100-4, 2002.

Denmead, O. T.: Approaches to measuring fluxes of methane and nitrous oxide between landscapes and the atmosphere, Plant Soil, 309, 5–24, doi:10.1007/s11104-008-9599-z, 2008.

Denmead, O. T. and Reicosky, D.: Tillage-induced gas fluxes: comparison of meteorological and large chamber techniques, In: Proceedings of the International Soil Tillage Research Organization 2003 conference, Brisbane, Australia, 13–18 July, 2003.

Desjardins, R. L.: Description and evaluation of a sensible heat flux detector, Bound.-Lay. Meteorol., 11, 147–154, doi:10.1007/BF02166801, 1977.

Dore, S., Hymus, G. J., Johnson, D. P., Hinkle, C. R., Valentini, R., and Drake, B. G.: Cross validation of open–top chamber and eddy covariance measurements of ecosystem CO_2 exchange in a Florida scrub-oak ecosystem, Global Change Biol., 9, 84–95, doi:10.1046/j.1365-2486.2003.00561.x, 2003.

Foken, T.: Micrometeorology, Springer, Berlin, 2008.

Foken, T. and Wichura, B.: Tools for quality assessment of surface based flux measurements, Agr. Forest Meteorol., 78, 83–105, 1996.

Foken, T., Göckede, M., Mauder, M., Mahrt, L., Amiro, B. D., and Munger, J. W.: Post-field data quality control, in: Handbook of micrometeorology: A guide for surface flux measurement and analysis, edited by: Lee, X., Massman, W., and Law B., Kluwer, Dordrecht, 181–208, 2004.

Foken, T., Aubinet, M., and Leuning, R.: The eddy-covariance method, in: Eddy Covariance: A Practical Guide to Measurement and Data Analysis, edited by: Aubinet, M., Vesala, T., and Papale, D., Springer, Dordrecht, Heidelberg, London, New York, 1–19, 2012a.

Foken, T., Leuning, R., Oncley, S. P., Mauder, M., and Aubinet, M.: Corrections and data quality, in: Eddy Covariance: A Practical Guide to Measurement and Data Analysis, edited by: Aubinet, M., Vesala, T., and Papale, D., Springer, Dordrecht, Heidelberg, London, New York, 85–131, 2012b.

Foken, T., Meixner, F. X., Falge, E., Zetzsch, C., Serafimovich, A., Bargsten, A., Behrendt, T., Biermann, T., Breuninger, C., Dix, S., Gerken, T., Hunner, M., Lehmann-Pape, L., Hens, K., Jocher, G., Kesselmeier, J., Lüers, J., Mayer, J.-C., Moravek, A., Plake, D., Riederer, M., Rütz, F., Scheibe, M., Siebicke, L., Sörgel, M., Staudt, K., Trebs, I., Tsokankunku, A., Welling, M., Wolff, V., and Zhu, Z.: Coupling processes and exchange of energy and reactive and non-reactive trace gases at a forest site – results of the EGER experiment, Atmos. Chem. Phys., 12, 1923–1950, doi:10.5194/acp-12-1923-2012, 2012c.

Fox, A. M., Huntley, B., Lloyd, C. R., Williams, M., and Baxter, R.: Net ecosystem exchange over heterogeneous Arctic tundra: Scaling between chamber and eddy covariance measurements, Global Biogeochem. Cy., 22, GB2027, doi:10.1029/2007GB003027, 2008.

Gao, W., Shaw, R. H., and Paw U, K. T.: Observation of organized structure in turbulent flow within and above a forest canopy, Bound.-Lay. Meteorol., 47, 349–377, doi:10.1007/BF00122339, 1989.

Göckede, M., Rebmann, C., and Foken, T.: A combination of quality assessment tools for eddy covariance measurements with footprint modelling for the characterisation of complex sites: Flux and concentration footprints, Agr. Forest Meteorol., 127, 175–188, doi:10.1016/j.agrformet.2004.07.012, 2004.

Göckede, M., Markkanen, T., Hasager, C. B., and Foken, T.: Update of a footprint-based approach for the characterization of complex measurement sites, Bound.-Lay. Meteorol., 118, 635–655, doi:10.1007/s10546-005-6435-3, 2006.

Goulden, M. L., Munger, J. W., Fan, S.-M., Daube, B. C., and Wofsy, S.: Measurements of carbon sequestration by long–term eddy covariance: methods and a critical evaluation of accuracy, Glob. Change Biol., 2, 169–182, doi:10.1111/j.1365-2486.1996.tb00070.x, 1996.

Holmes, P., Lumley, J. L., Berkooz, G., and Rowley, C. W.: Turbulence, coherent structures, dynamical systems and symmetry, 2nd Edn., Cambridge University Press, Cambridge, UK, New York, 386 pp., 2012.

Janssens, I. A., Kowalski, A. S., and Ceulemans, R.: Forest floor CO_2 fluxes estimated by eddy covariance and chamber–based model, Agr. Forest Meteorol., 106, 61–69, 2001.

Karipot, A., Leclerc, M. Y., Zhang, G., Lewin, K. F., Nagy, J., Hendrey, G. R., and Starr, D.: Influence of nocturnal low-level jet on turbulence structure and CO_2 flux measurements over a forest canopy, J. Geophys. Res., 113, D10102, doi:10.1029/2007JD009149, 2008.

Kimball, B. and Lemon, E. R.: Air Turbulence Effects upon Soil Gas Exchange, Soil Sci. Soc. Am. J., 35, 16–21, 1971.

Kimball, B. and Lemon, E. R.: Theory of soil air movement due to pressure fluctuations, Agric. Meteorol., 9, 163–181, 1972.

Kutzbach, L., Schneider, J., Sachs, T., Giebels, M., Nykänen, H., Shurpali, N. J., Martikainen, P. J., Alm, J., and Wilmking, M.: CO_2 flux determination by closed-chamber methods can be seriously biased by inappropriate application of linear regression, Biogeosciences, 4, 1005–1025, doi:10.5194/bg-4-1005-2007, 2007.

Lai, D. Y. F., Roulet, N. T., Humphreys, E. R., Moore, T. R., and Dalva, M.: The effect of atmospheric turbulence and chamber deployment period on autochamber CO_2 and CH_4 flux measurements in an ombrotrophic peatland, Biogeosciences, 9, 3305–3322, doi:10.5194/bg-9-3305-2012, 2012.

Laine, A., Sottocornola, M., Kiely, G., Byrne, K. A., Wilson, D., and Tuittila, E.-S.: Estimating net ecosystem exchange in a patterned ecosystem: Example from blanket bog, Agr. Forest Meteorol., 138, 231–243, doi:10.1016/j.agrformet.2006.05.005, 2006.

Lee, X., Massman, W. J., and Law, B. (Eds.): Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis, Kluwer, Dordrecht, 250 pp., 2004.

LI-COR: LI-8100 Instruction Manual, LI-8100 automated soil CO_2 flux system, LI-COR, Inc., Lincoln, NE, USA 68504, 2004.

Mauder, M. and Foken, T.: Documentation and instruction manual of the eddy covariance software package TK2, Univ. Bayreuth, Abt. Mikrometeorol., ISSN: 1614-89166, 26, 42 pp., 2004.

Mauder, M. and Foken, T.: Documentation and instruction manual of the eddy covariance software package TK3, Univ. Bayreuth, Abt. Mikrometeorol., ISSN: 1614-89166, 46, 58 pp., 2011.

Mauder, M., Foken, T., Clement, R., Elbers, J. A., Eugster, W., Grünwald, T., Heusinkveld, B., and Kolle, O.: Quality control of CarboEurope flux data – Part 2: Inter-comparison of eddy-covariance software, Biogeosciences, 5, 451–462, doi:10.5194/bg-5-451-2008, 2008.

Moncrieff, J., Valentini, R., Greco S., Seufert, G., and Ciccioli P.: Trace gas exchange over terrestrial ecosystems: Methods and perspectives in micrometeorology, J. Exp. Bot., 48, 1133–1142, 1997.

Montgomery R. B.: Vertical eddy flux of heat in the atmosphere, J. Meteorol., 5, 265–274, 1948.

Myklebust, M., Hipps, L., and Ryel, R.: Comparison of eddy covariance, chamber, and gradient methods of measuring soil CO_2 efflux in an annual semi-arid grass, Bromus tectorum, Agr. Forest Meteorol., 148, 1894–1907, doi:10.1016/j.agrformet.2008.06.016, 2008.

Norman, J. M., Kucharik, C. J., Gower, S. T., Baldocchi, D. D., Crill, P. M., Rayment, M., Savage, K., and Striegl, R. G.: A comparison of six methods for measuring soil–surface carbon dioxide fluxes, J. Geophys. Res., 102, 28771–28777, 1997.

Obukhov, A. M.: Charakteristiki mikrostruktury vetra v prizemnom sloje atmosfery (Characteristics of the micro-structure of the wind in the surface layer of the atmosphere), Izv AN SSSR, ser Geofiz., 3, 49–68, 1951.

Pumpanen, J., Kolari, P., Ilvesniemi, H., Minkkinen, K., Vesala, T., Niinistö, S., Lohila, A., Larmola, T., Morero, M., Pihlatie, M., Janssens, I., Yuste, J. C., Grünzweig, J. M., Reth, S., Subke, J.-A., Savage, K., Kutsch, W., Østreng, G., Ziegler, W., Anthoni, P., Lindroth, A., and Hari, P.: Comparison of different chamber techniques for measuring soil CO_2 efflux, Agr. Forest Meteorol., 123, 159–176, doi:10.1016/j.agrformet.2003.12.001, 2004.

Rannik, Ü., Aubinet, M., Kurbanmuradov, O., Sabelfeld, K. K., Markkanen, T., and Vesala, T.: Footprint analysis for measurements over a heterogeneous forest, Bound.-Lay. Meteorol., 97, 137–166, doi:10.1023/A:1002702810929, 2000.

Rannik, Ü., Sogachev, A., Foken, T., Göckede, M., Kljun, N., Leclerc, M. Y., and Vesala, T.: Footprint Analysis, in: Eddy Covariance: A Practical Guide to Measurement and Data Analysis, edited by: Aubinet, M., Vesala, T., and Papale, D., Springer Netherlands, Dordrecht, 211–261, 2012.

Reth, S., Göckede, M., and Falge, E.: CO_2 efflux from agricultural soils in Eastern Germany – comparison of a closed chamber system with eddy covariance measurements, Theor. Appl. Climatol., 80, 105–120, doi:10.1007/s00704-004-0094-z, 2005.

Rochette, P. and Hutchinson, G. L.: Measurement of Soil Respiration in situ: Chamber Techniques, in: Micrometeorology in agricultural systems, edited by: Hatfield, J. L. and Baker, J. M., American Society of Agronomy; Crop Science Society of America; Soil Science Society of America, Madison, Wisconsin, 247–287, 2005.

Serafimovich, A., Thomas, C., and Foken, T.: Vertical and Horizontal Transport of Energy and Matter by Coherent Motions in a Tall Spruce Canopy, Bound.-Lay. Meteorol., 140, 429–451, doi:10.1007/s10546-011-9619-z, 2011.

Stull, R. B.: An introduction to boundary layer meteorology, Kluwer Academic Publishers, Dordrecht, Boston, xii, 666, 1988.

Subke, J.-A. and Tenhunen, J. D.: Direct measurements of CO_2 flux below a spruce forest canopy, Agr. Forest Meteorol., 126, 157–168, doi:10.1016/j.agrformet.2004.06.007, 2004.

Swinbank W. C.: The measurement of vertical transfer of heat and water vapor by eddies in the lower atmosphere, J. Meteorol., 8, 135–145, 1951.

Thomas, C. and Foken, T.: Detection of long–term coherent exchange over spruce forest using wavelet analysis, Theor. Appl. Climatol., 80, 91–104, doi:10.1007/s00704-004-0093-0, 2005.

Thomas, C. and Foken, T.: Flux contribution of coherent structures and its implications for the exchange of energy and matter in a tall spruce canopy, Bound.-Lay. Meteorol., 123, 317–337, doi:10.1007/s10546-006-9144-7, 2007.

van Gorsel, E., Leuning, R., Cleugh, H. A., Keith, H., and Suni, T.: Nocturnal carbon efflux: reconciliation of eddy covariance and chamber measurements using an alternative to the u_* – threshold filtering technique, Tellus B, 59, 397–403, doi:10.1111/j.1600-0889.2007.00252.x, 2007.

Vickers, D. and Mahrt, L.: Quality control and flux sampling problems for tower and aircraft data, J. Atmos. Ocean. Tech., 14, 512–526, 1997.

Wang, K., Liu, C., Zheng, X., Pihlatie, M., Li, B., Haapanala, S., Vesala, T., Liu, H., Wang, Y., Liu, G., and Hu, F.: Comparison between eddy covariance and automatic chamber techniques for measuring net ecosystem exchange of carbon dioxide in cotton and wheat fields, Biogeosciences, 10, 6865–6877, doi:10.5194/bg-10-6865-2013, 2013.

Wang, M., Guan, D.-X., Han, S.-J., and Wu, J.-L.: Comparison of eddy covariance and chamber-based methods for measuring CO_2 flux in a temperate mixed forest, Tree Physiol., 30, 149–163, doi:10.1093/treephys/tpp098, 2009.

Werle, P. and Kormann, R.: Fast Chemical Sensor for Eddy-Correlation Measurements of Methane Emissions from Rice Paddy Fields, Appl. Optics, 40, 846–858, doi:10.1364/AO.40.000846, 2001.

Wohlfahrt, G., Klumpp K., and Soussana, J. F.: Eddy covariance measurements over grasslands, in: Eddy Covariance: A practical guide to measurement and data analysis, edited by: Aubinet, M., Vesala, T., and Papale, D., Springer, Dordrecht, Heidelberg, London, New York, 333–344, 2012.

Xu, L., Furtaw, M. D., Madsen, R. A., Garcia, R. L., Anderson, D. J., and McDermitt, D. K.: On maintaining pressure equilibrium between a soil CO_2 flux chamber and the ambient air, J. Geophys. Res., 111, D08S10, doi:10.1029/2005JD006435, 2006.