Contribution of advection to nighttime ecosystem respiration at a mountain grassland in complex terrain

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Abstract

Net ecosystem carbon dioxide (CO₂) exchange (NEE) at FLUXNET sites is typically evaluated by means of the eddy covariance technique using a set of instruments on a single tower. However, in complex terrain, such as mountain areas, and during nighttime atmospheric conditions, with low turbulent mixing and stable stratification, this approach is known to underestimate the nighttime NEE and thus bias longer-term carbon balances. This study reports on the quantification of advection at a subalpine grassland site in Northern Italy (2160 m asl) situated in complex mountainous terrain. We show that different published methods for indirectly or directly accounting for advection resulted in a large divergence in the annual carbon balance. Advection, and in particular the horizontal term, reached non negligible values during nighttime and its inclusion in the CO₂ conservation equation increased NEE by a factor of two. NEE calculated by taking into account all terms (NEEacmb), i.e. turbulent exchange, change in storage and advection of CO₂, matched the approach based on the after-sunset maximum in the vertical turbulent flux and change in the storage of CO₂ and ecosystem respiration measured by automated chambers. Accounting for advection led to a 169% change in the annual carbon budget, turning the ecosystem from a sink (-108 gCm⁻²y⁻¹) to a source (75 gCm⁻²y⁻¹) of CO₂.

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1. Introduction

The increase in the atmospheric concentration of carbon dioxide (CO$_2$) since 1750 is the major factor responsible for the observed global warming (Stocker et al., 2013). Since a percentage (∼40-45%) of the anthropogenically emitted CO$_2$ remains in the atmosphere, while a part is captured by ocean and land sinks (Le Quéré et al., 2009), particular attention of the scientific community has been devoted to assessing the role of several ecosystems to the global carbon cycle (Baldocchi, 2014).

A widely used method to quantify the net exchange of CO$_2$ (NEE) between ecosystems and the atmosphere is the eddy covariance (EC) technique, which operates at the appropriate spatial scale of the ecosystem and covers temporal scales from hours to decades (Baldocchi, 2003). These characteristics make the EC method an invaluable tool for studying the long-term gas exchange processes and to determine if an ecosystem acts as a sink or a source of CO$_2$ and how this role could be modified by climate change. Nevertheless, the EC method is prone to some critical issues (Aubinet, 2008), which must be taken into account, primarily when the aim of the study is to determine the net amount of carbon that is sequestered or emitted by an ecosystem during a given timespan.

The EC method assesses the source/sink term of the CO$_2$ conservation equation assuming that it can be inferred from the vertical turbulent exchange and the change in the storage term, thereby considering the remaining components, i.e. the vertical and horizontal advection and the divergence of the turbulent flux, negligibly small (Finnigan 1999; Aubinet et al. 2000). This approach relies on the assumption that the mass balance of CO$_2$ mixing ratio of an ecosystem can be approximated by a single point measurement when the requirements of stationary conditions, high turbulent mixing, flat, and horizontally homogeneous terrain are satisfied (Baldocchi et al. 2000; Aubinet et al. 2003; Marcolla et al.)
During stable and calm nighttime conditions, and in particular in complex terrain these requirements are however likely to be violated and the advective terms of the conservation equation become non-negligible, resulting in an underestimation of the nocturnal NEE (Baldocchi et al. 2000; Aubinet et al. 2010; Vickers et al. 2012). Since the daily net exchange of CO$_2$ is composed by net uptake during daytime, when plant photosynthesis exceeds respiration, and net emission of CO$_2$ during nighttime due to ecosystem respiration, the unaccounted advective fluxes may potentially bias the net daily and longer-term flux measurements towards a systematically overestimated net CO$_2$ sequestration (Goulden et al. 1996; Moncrieff et al. 1996).

Common approaches to overcome the nighttime underestimation are based on the rejection of data measured when the theoretical requirements are not fulfilled. The widely used engineering-type approach consists in discarding data measured during calm conditions, i.e. below a site-specific threshold of friction velocity ($u^*$) and replacing these with values estimated from an empirical relationship between the remaining NEE data (under windy conditions) and environmental parameters (Falge et al. 2001a,b; Reichstein et al. 2005; Papale et al. 2006). Acevedo et al. (2009) pointed to uncertainties related to this threshold and proposed the use of the standard deviation of the vertical wind velocity ($w$) instead of $u^*$. van Gorsel et al. (2007) presented another alternative method, which takes advantage of the early evening maximum in the vertical turbulent flux and change in the storage of CO$_2$, resulting from the interval between sunset and the onset of advection. The authors proposed to derive an empirical model based on the early evening maximum in NEE and independent variables, such as air and soil temperature, which is then used to estimate nighttime respiration. However, since substituting nighttime NEE measured during calm conditions with NEE estimated using observations made under windy periods potentially propagates errors, each of the described methods may increase NEE uncertainty (Baldocchi 2003; Acevedo et al. 2009). Alternatively, all terms contributing to the nighttime carbon exchange can be measured, making corrections during non-turbulent periods unnecessary. This approach, coined *advection completed mass*
balance (ACMB) by Aubinet et al. (2010), requires additional measurements of wind speed and horizontal/vertical CO$_2$ gradients. Since natural ecosystems, and in particular mountain sites, are often located in complex terrain, the evaluation of the full CO$_2$ mass balance has recently received increasing attention (e.g. Marcolla et al. 2005; Aubinet et al. 2010; Feigenwinter et al. 2008; Montagnani et al. 2010). However, multiple towers and complex arrays of instruments are generally required for running these measurements, which are costly and difficult to be maintained with a long-term perspective (Aubinet et al. 2010; Marcolla et al. 2014). Previous advection experiments have been conducted almost exclusively in forest ecosystems and, to our knowledge, only little information exists for low stunted vegetation where advection is often supposed to play a minor role (Hiller et al., 2008). However, grasslands may have a large practical advantage compared to forests, since measurements of advection can be realised with smaller infrastructure and thus with less experimental and economic effort. Reporting on the role of neglected advective fluxes in grassland ecosystems is of foremost importance to contribute towards reducing the uncertainty of current NEE global estimates and on the surface energy imbalance problem (Leuning et al., 2012), as these ecosystems cover 40% of land surface (White et al., 2000). In addition, grassland ecosystems are characteristic elements of worldwide mountain areas, which, with their global distribution and the sensitivity to both human and environmental changes represent invaluable reference points in climate change research (Körner, 2003). Because mountain terrain with its complex orography and fragmented nature is prone to the development of adverse conditions for micrometeorological studies (Rotach et al., 2014), such as nocturnal gravity flows, EC measurements in these locations have been historically discouraged. Nevertheless, previous studies (Etzold et al., 2010) demonstrated that the typical bi-directional wind pattern, such as diurnal slope or valley winds (Whiteman 2000; Hammerle et al. 2007; Wohlfahrt et al. 2016), makes the set-up of advection studies less challenging than in some flat area (e.g. Aubinet et al. 2010).

Advances in respiration chambers technology allow to compare EC-based
nighttime NEE with independent measurements of ecosystem respiration. However, uncertainties exist when upscaling observations from leaf to canopy or ecosystem scale or if temporally discrete manual measurements are performed. Automated chambers are easier to use in low canopies, where the main sources of uncertainty could be represented by the system design and the small-scale spatial variability in the sources/sinks of CO₂ (Baldocchi 2014; Görres et al. 2015).

In this paper we present a proof-of-concept study, which aims at illustrating the first quantification of the contribution of advective fluxes to the CO₂ budget measured by EC at a subalpine grassland in the Alps. The specific objectives of the study were: i) to quantify the advective fluxes with a simplified 2-D approach, ii) to illustrate the comparison among different EC-based and chamber-based NEE calculations to obtain the nocturnal respiration at our site and iii) to extrapolate advection data to years not covered by direct measurements.

2. Materials and Methods

2.1. Study site

The Torgnon site (FLUXNET site name IT-Tor) is a subalpine unmanaged grassland located in the northwestern Italian Alps at an elevation of 2160 m asl (45°50’40” N, 7°34’41” E). Dominant vegetation mainly consists of matgrass, (Nardus stricta) with Arnica montana, Trifolium alpinum and Carex sempervirens as co-dominant species. During the growing season, the peak value of leaf area index (LAI) is on average 2.2 m²m⁻² and maximum canopy height is 20 cm. The site is characterized by a mean annual temperature of 3.1 °C and mean annual precipitation of about 880 mm. On average, the site is covered by snow (up to 90-120 cm of snow depth) from the end of October to late May, which limits the growing season to an average of five months. While the average terrain slope is less than 5°, with a total difference in altitude of 22 meters, the site is characterized by undulating terrain with slopes at various angles and
expositions (Fig. 1). Regular eddy covariance (EC) measurements of CO₂ flux are carried out continuously since June 2008 (Galvagno et al. 2013). In this study, data of the years 2010, 2011, 2012 and 2014 were used for the analysis.

2.2. Permanent and experimental EC setups

The permanent instrumental setup at the site consists of an eddy covariance system (hereinafter labeled EC-1, Fig. 1) composed by a CSAT3 three-dimensional sonic anemometer (Campbell Scientific, Inc.) for measurement of wind speed in the three components \((u, v, w)\) and the sonic temperature, and a LI-7500 open-path infrared gas analyzer (LI-COR, Inc.) for measurements of CO₂ and H₂O air densities. Instruments were placed 1.65 m above the ground and measurements were performed at a frequency of 10 Hz. A weather station provided 30-min averaged records of different meteorological parameters, including air and soil temperature (HMP45, Vaisala Inc. and therm107, Campbell Scientific, Inc.), and global radiation (CNR4, Kipp and Zonen Corp.). Further details on the site instrumental system are found in Galvagno et al. (2013).

To evaluate the contribution of advection to the carbon balance of this grassland, in summer 2012 an additional eddy covariance system (EC-2) and measurements of wind speed and CO₂ concentrations (see section 2.3) were set up. EC-2 was equipped with sensors equivalent to EC-1, and an additional two-dimensional sonic anemometer (WindSonic, Gill) placed at 0.90 m above the ground. EC-2 was sequentially (from 31 July to 10 August and from 10 to 21 August) placed at two different locations of the site, to account for potential spatial differences in the contribution of advection (Fig. 1).

2.3. CO₂ concentration profiles and automated chambers

The LI-8100/8150 profiling system (LI-COR, Inc.) was used to obtain horizontal and vertical profiles of CO₂ concentrations. In detail, CO₂ concentration was measured over two vertical profiles with three sample points each (0.30, 0.90, 1.65 m), installed 30 meters uphill and downhill the EC-2 tower with the following scheme: 1. uphill 1.65 m - downhill 1.65 m; 2. uphill 0.90 m - downhill
0.90 m; 3. uphill 0.30 m - downhill 0.30 m. The transect was aligned NE-SW (45-200°), the main wind direction (Fig. 1). The 6 inlets were consecutively sampled for CO₂ concentration with an observation length of 1 min using an air flow of 3 l min⁻¹. A purging period of 15 seconds was set in order to prevent contamination between two sequential measurements. In any measurement cycle each point was sampled twice and then averaged to a half-hourly value.

In order to obtain independent measures of ecosystem respiration, four automated opaque CO₂ flux chambers (model 8100-104, LI-COR, Inc.) were installed near the advection transects during the advection campaign and near EC-1 in all the other years. Being applied in a low-canopy site, this enclosure system allows estimating ecosystem respiration directly without the need for upscaling component CO₂ flux measurements (Görres et al., 2015). CO₂ flux from the automated chambers was derived as the rate of change of CO₂ mixing ratio in the measurement chamber according to the manufacturer software, and data were considered as outliers and removed when the coefficient of determination of the gradient fit was lower than 0.99. The instrument was calibrated prior to the field campaign. Because each chamber sampled a small area, differences between chambers can occur due to small-scale spatial variability in the sources/sinks of CO₂ fluxes. The coefficient of variation (CV) was quantified taking into account standard deviations among the four chambers for the whole study period, and averaged to 18% (mean standard deviation, 1.1 µmol m⁻² s⁻¹, for further details refer to the Appendix).

2.4. EC data processing

Half-hourly eddy fluxes (EC-1, EC-2) were calculated by computing the mean covariance between vertical wind speed and CO₂ densities (Baldocchi, 2003), and following the standard procedures as reported by the Euroflux methodology for both raw data processing and quality check (Aubinet et al. 2000; Mauder and Foken 2004). The planar-fit method was performed for each location of the experimental campaign to correct the anemometer tilt with respect to the mean wind streamlines (Wilczak et al., 2001). The density effect on flux
measurements due to heat and water vapor fluctuations was corrected using the method described in Webb et al. (1980), while frequency response corrections were applied in order to account for spectral loss in the high frequency and low frequency range following Moore (1986) and Aubinet et al. (2010). In this study the term $F_c$ represents the vertical turbulent CO$_2$ flux and $F_s$ is the storage term. $F_s$ was computed as the time rate of change of the CO$_2$ mixing ratio at the measurement height for EC-1 and from the profiling system for EC-2 as described in section 2.5. In this study the convention by which negative fluxes correspond to a net CO$_2$ movement from the atmosphere to the biosphere and positive values the reverse was used. Commonly applied tests (i.e. integral turbulence characteristics and stationarity tests, Foken and Wichura (1996)) were applied to check the quality of the vertical turbulent flux and combined to an overall flag to filter the flux dataset.

2.5. Mass balance terms

For the theoretical background underlying the advection calculation and further details concerning the following paragraph we refer to the specific bibliography (Baldocchi et al. 2000; Finnigan 1999; Massman and Lee 2002; Aubinet et al. 2003).

We took advantage of the bi-directional wind pattern and simple canopy at this site to calculate advection in a simplified two-dimensional (2D) form (Feigenwinter et al., 2004), as previously applied in other studies (e.g. Aubinet et al. 2003; Marcolla et al. 2005; Etzold et al. 2010). The CO$_2$ mixing ratio measured by the profiling system along the vertical and horizontal transects were combined with wind speed data from the 3D and 2D EC-2 anemometers to compute the advection terms by means of a 5-point Gaussian quadrature rule. Wind speed was extrapolated at the 5 gaussian heights (0.08, 0.38, 0.83, 1.27, 1.57 m) by applying a logarithmic wind profile above the canopy and an exponential equation below the canopy following the method described in Wohlfahrt et al. (2000). CO$_2$ mixing ratios were extrapolated at the same heights by applying a linear fitting. Horizontal advection ($F_{ha}$) was computed
as:

\[ F_{ha} = \int_0^{1.65} \bar{\nu}(z) \frac{\partial \nu(z)}{\partial x} dz \]  

(1)

where, \( \bar{\nu} \) is the along transect mean wind component, \( z \) represents the measurement and integration height and \( \frac{\partial \nu}{\partial x} \) is the horizontal gradient of CO₂ mixing ratio. By restricting our observations to conditions where the \( \bar{\nu} \) direction does not exceed the profile alignment (45-200°) by more than 18°, we limited the uncertainty on the gradient measured by the proposed 2D approach to less than 5%, based on the trigonometrical calculations derived from Etzold et al. (2010).

The vertical advection term (\( F_{va} \)) was computed as the product of the mean vertical wind component, \( \nu_{h1.65} \) at the measurement height \( h_{1.65} \), and the difference between the CO₂ mixing ratio at 1.65 m, \( c_{h1.65} \), and the mean CO₂ concentration in the control volume, \( c \) (Lee 1998; Feigenwinter et al. 2004):

\[ F_{va} = \nu_{h1.65}(\bar{c}_{h1.65} - \bar{c}) \]  

(2)

where, \( \bar{c} = \frac{1}{h} \int_0^{1.65} \nu(z) dz \)  

(3)

Finally the storage term (\( F_c \)) for EC-2 was computed as follows:

\[ F_c = \int_0^{1.65} \frac{\partial \nu}{\partial t} dz \]  

(4)

where \( \frac{\partial \nu}{\partial t} \) represents the time rate of change of CO₂ mixing ratio.

In order to quantify the measurement uncertainty related to our advection measurement system, the standard errors of half-hourly CO₂ mixing ratio and wind components, the accuracy of the instruments and the 5% error related to the transect alignment, were computed. The individual uncertainties were propagated into the advection calculations to obtain the \( F_{ha} \) and \( F_{va} \) measurement errors following error propagation rules (Hughes and Hase, 2010).

2.6. NEE calculation

In this study we tested the contribution of different calculation options on nighttime NEE measured during the 2012 campaign. NEE was firstly computed
as the sum of $F_c$ and $F_s$ measured by EC-2:

$$\text{NEE} = F_c + F_s$$ (5)

Different NEE calculations were then obtained in accordance with the following different approaches:

- $\text{NEE}_{u^*}$: nighttime NEE was filtered according to the $u^*$ threshold of 0.05 $\text{ms}^{-1}$ (Galvagno et al., 2013), computed based on Papale et al. (2006). Nighttime hours were selected using a global radiation ($R_g$) threshold of 20 $\text{Wm}^{-2}$.

- $\text{NEE}_{\sigma_w}$: nighttime NEE was filtered as described above, but using the turbulence scale of $\sigma_w$ instead of $u^*$ (Acevedo et al., 2009) with a threshold value of 0.09 $\text{ms}^{-1}$.

- $R_{\text{max}}$: nighttime NEE computed from the maximum value of $F_c+F_s$ after sunset as suggested by van Gorsel et al. (2008).

- $\text{NEE}_{\text{acmb}}$: in this approach the “advection completed mass balance” was estimated by adding the measured advective terms (section 2.5) to nighttime NEE, as follows:

$$\text{NEE}_{\text{acmb}} = F_c + F_s + F_{ha} + F_{va}$$ (6)

- $\text{NEE}_{\text{Fmod}}$: we investigated the relation of $F_{ha}+F_{va}$ with $u^*$ in order to derive an estimation of advection ($F_{mod}$), related to turbulence conditions independent from direct measurements. $F_{mod}$ was then summed to $F_c+F_s$ to obtain $\text{NEE}_{\text{Fmod}}$.

- $R_{\text{cham}}$: nighttime NEE derived from the opaque chambers.

To obtain continuous NEE time-series each dataset was gap-filled according to Reichstein et al. (2005). Furthermore, two independent and standard estimates of filtered and gapfilled NEE were derived from the FLUXNET2015 dataset (http://fluxnet.fluxdata.org/data/fluxnet2015-dataset/)

- $\text{NEE}_{u^*50}$: NEE filtered using 50-percentile of $u^*$ thresholds from bootstrapping. The $u^*$ threshold is variable for each year.

- $\text{NEE}_{\text{REF}}$: NEE filtered using the $u^*$ threshold extracted from the model efficiency approach and variable for each year.
Finally, we considered the uncertainty related to the $u^*$ threshold determination available from the FLUXNET2015 dataset, and expressed it as interquartile range, IQR (i.e. the difference between NEE filtered using the 75th percentile and 25th percentile of $u^*$ thresholds).

Since incorporating the advection terms in the CO$_2$ mass balance equation is still an issue (Aubinet et al., 2010), the eight described approaches were in addition applied to the full available EC-1 yearly datasets (2010, 2011, 2012, 2014) to evaluate the impact that individual methods, and in particular the unaccounted advection, may have on the annual budgets. To this aim our approaches were firstly tested on two independent validation datasets, i.e. different from the experimental one, the growing seasons of 2010 (128 days) and 2014 (168 days), during which also chamber measurements were available. Yearly NEE$_{u^*}$, NEE$_{σw}$, R$_{max}$ were computed for each year separately, NEE$_{u^*50}$ and NEE$_{REF}$ were directly obtained from the FLUXNET2015 dataset, while NEE$_{Fmod}$ was estimated on the basis of data collected during the field campaign in 2012 and extrapolated to other years. Since the presence and transformation of snow-cover change the physical properties of the atmosphere-vegetation interface, thereby influencing the above fluxes (Armstrong and Brun, 2008), with the current dataset it was not possible to obtain information on the advective processes during the winter season, consequently, only the snow-free period was corrected, while winter NEE data was not corrected for all the datasets, except for NEE derived from FLUXNET2015, which was used precisely as provided from the database.

3. Results

3.1. Atmospheric conditions

In this section the average atmospheric conditions at the site are presented considering both the entire study period (growing season) from 2010 to 2014 and the data of the 2012 experimental campaign. The prevailing wind directions at the site (Fig. 1, 2) showed a typical bi-directional pattern, with SE (180-220°)
and NW (20-70°) winds dominating during daytime (65%) and nighttime (83%), respectively. The shift from South-East to North-West winds was sharp at the transition from day to night hours (Fig. 2). This time of the day (around 19.00 CET) indicated the transition to reduced turbulence with low wind speeds and $u^*$, which showed values below 1.2 and 0.1 ms$^{-1}$ respectively, and an increase of atmospheric stability ($z/L > 0$, Monin-Obukhov parameter), indicating that stable stratification dominated during nighttime. Conversely, during daytime both wind speed and $u^*$ showed high values around 2 and 0.3 ms$^{-1}$ respectively, and $z/L$ was lower than 0, indicating well-developed convective turbulence.

3.2. Advection data and correction approaches

Wind and CO$_2$ profiles sampled during the advection campaign in 2012 indicated a good turbulent mixing during daytime when wind velocity is generally high and CO$_2$ mixing ratio is invariable in the vertical (height above the ground) and horizontal (uphill, downhill) space (Fig. 3). Conversely, during nighttime the accumulation of CO$_2$ in the air column and the difference between the uphill and downhill profiles (∼ 4 ppm), associated with lower wind speed, set the conditions for the non-turbulent transport processes. The mean diurnal variation of each term of Eq. (6), is shown in Figure 4. Advection data confirmed that the CO$_2$ mass balance was influenced by nocturnal horizontal flows that moved CO$_2$ out from the control volume. The daily pattern of advection closely reflected that of the wind speed, $u^*$ and $z/L$ presented in Figure 2. The turbulent term $F_c+F_s$ showed a nighttime efflux of 3 μmolm$^{-2}$s$^{-1}$ and diverged from the automated chambers, which, with an average flux of 6 μmolm$^{-2}$s$^{-1}$, exceeded $F_c+F_s$ values by almost 100%. During nighttime $F_{ha}$ clearly exceeded $F_{va}$ which fluctuated around zero, while both advection terms were close to zero during daytime. An average horizontal advective flux of 3 μmolm$^{-2}$s$^{-1}$ was observed during the night hours from around 20.00 to 06.00 CET, similar in magnitude to $F_c+F_s$. Around sunset (19.00 CET), just before the set up of calm conditions, $F_{ha}$ showed minimum values, concurrent with high values of $F_s$. When summing $F_{ha}+F_{va}$ to $F_c+F_s$, the new term corresponded with
chamber records during the night hours and with F_c+F_s during daytime (Fig. 4). Since the campaign was conducted in two different locations sequentially, shaded areas in Figure 4 represent for each term the combined temporal and spatial variability during the study period, expressed as 95% confidence intervals (i.e. CI, 1.96 times the standard error of the mean of measurements carried on in the two periods and locations). Even if in some cases the temporal/spatial variability is large (e.g. for F_c+F_s+F_ha+F_va), the CI of the different terms traced the described differences and similarities and showed the same diurnal course among calculations, indicating that the variability is mainly related to changing environmental/phenological conditions during the study period. A presentation of measurements conducted in the first and the second location (and period), separately, can be found in the Appendix, confirming that spatial variability played a minor role.

Both turbulent and advective terms showed constant values (slope not significantly different from zero) with the variation of u* as an indication of mechanical turbulence (Fig. 5). Based on these results the term NEE_{Fmod}, introduced in section 2.6 was calculated as the sum of F_c+F_s and the average of F_ha+F_va (i.e. 3 \mu molm^{-2}s^{-1}). Figure 6 shows the effect of the different processing approaches on the nighttime CO_2 efflux. The two filtering methods NEE_{u*}, and NEE_{\sigma_w}, resulted in mean nocturnal fluxes of 3, and 3.7 \mu molm^{-2}s^{-1}, respectively, that did not significantly differ (Tukey HSD, p<0.05) from uncorrected NEE data (3 \mu molm^{-2}s^{-1}) and were lower than those of the standard filtering methods NEE_{50%} and NEE_{REF} (4.0 \mu molm^{-2}s^{-1}), R_{max} (5.7 \mu molm^{-2}s^{-1}), the advection methods (NEE_{acmb}, NEE_{Fmod}, 5.7 and 5.8 \mu molm^{-2}s^{-1}) and the automated chambers (6 \mu molm^{-2}s^{-1}). The use of NEE_{50%} and NEE_{REF} provided NEE estimates, which were higher than NEE_{u*} and NEE_{\sigma_w}, but differed significantly from the advection methods and the automated chambers. R_{max} was closer to both the advection methods and R_{cham}, however, it did not significantly differ from the previous terms NEE_{50%} and NEE_{REF}. Taking into account direct advection measurements resulted in nighttime CO_2 fluxes (NEE_{acmb}) which significantly deviated from all the filtering methods but agreed
with \( R_{max} \) and the independent chambers measurements. Figure 6 shows that NEE_{Fmod} successfully performed in providing good agreement with direct advection measurements (NEE_{acmb}) and consequently with \( R_{max} \) and \( R_{cham} \).

### 3.3. Contribution of advection to annual budgets and uncertainty

\( F_{mod} \) was fixed to 3.3 \( \mu \text{mol m}^{-2} \text{s}^{-1} \) during the 2012 summer campaign, however this value is likely to overestimate the true advective flux at the edges of the season when CO\(_2\) efflux from the ecosystem is lower. In order to account for the seasonal variability of the fluxes, NEE_{Fmod} for the annual analysis was computed as the sum of NEE and the percentage of \( F_{mod} \) to NEE measured during the field campaign. The comparison of the approaches to calculate NEE in years different from the experimental one (2010, 2014; Table 1) indicates that the methods separated into two groups with regard to the nighttime values, the first with NEE, NEE\(_{u*}\), NEE\(_{\sigma w}\), NEE\(_{50\%}\) and NEE\(_{REF}\) yielding lower sums compared to the second represented by \( R_{max} \), NEE\(_{Fmod} \) and \( R_{cham} \). The seasonal course of nighttime NEE observed during the two growing season (Fig.7) highlights the good agreement between NEE\(_{Fmod} \) and \( R_{cham} \). Conversely, even though \( R_{max} \) closely matched NEE\(_{Fmod} \) and \( R_{cham} \) when integrated over the whole growing season, this approach was weaker in representing the amplitude of short-term variations in ecosystem respiration. The Taylor diagram in Figure 8 shows that the different approaches correlated in a similar fashion (R\( \sim 0.75 \)) with \( R_{cham} \), but only NEE\(_{Fmod} \) showed an amplitude of variations in fluxes similar to chambers (standard deviation equal to 2.1 \( \mu \text{mol m}^{-2} \text{s}^{-1} \)).

Table 2 shows the contribution of the different NEE correction approaches to the annual budgets of the grassland ecosystem from 2010 to 2014. For all the considered years the NEE\(_{u*}\) method (-107 gCm\(^{-2}\)y\(^{-1}\)) did not significantly affect the annual budget as compared to uncorrected NEE (-108 gCm\(^{-2}\)y\(^{-1}\)), while all the other approaches led to less negative or positive annual sums. The yearly NEE\(_{\sigma w}\) diverged from uncorrected NEE on average by 32 gCm\(^{-2}\)y\(^{-1}\), NEE\(_{50\%}\) and NEE\(_{REF}\) with a mean difference of 70 gCm\(^{-2}\)y\(^{-1}\), led the annual carbon balance close to neutrality, while \( R_{max} \) and NEE\(_{Fmod} \) added to the
original NEE on average 168 and 183 gCm\(^{-2}\)y\(^{-1}\) respectively. The use of the last two methods thus shifted the ecosystem from a sink to a source in all the considered years but 2011, which was an extremely productive year (Galvagno et al., 2013). The interquartile range of standard NEE estimates for the seasonal and annual sums (Tables 1, 2) was on average 48 and 58 gCm\(^{-2}\)y\(^{-1}\), respectively, consequently the use of the 75th percentile of u* thresholds could lead to greater sums, however the budgets obtained with \(R_{max}\), \(NEE_{Fmod}\) and \(R_{cham}\) were placed outside the upper limit of this range. Detailed information about seasonal and annual sums obtained with different percentile of u* thresholds is given in table A.1 of the Appendix.

Though each of the methods tested generated a different quantity of gaps related to the specific filtering strategy, the comparison of mean and distribution of the various NEE calculations before and after the gap-filling, revealed that the role of the latter made a minor contribution compared to the within-methods difference (not shown).

4. Discussion

Quantification of advection in a short-statured canopy with a 2D approach

The study reports on the first attempt of quantifying advection of CO\(_2\) in a short-statured canopy ecosystem, an unmanaged grassland of the Italian Alps. Grassland canopies are often assumed to be less affected by advection due to their short stature and, for this reason, little information exists on the potential underestimation of nighttime CO\(_2\) fluxes measured with the eddy covariance technique in these ecosystems (Twine et al. 2000; Hiller et al. 2008).

The main findings of this study (Figs. 4-8) can be summarised as follows: (i) the sum of the vertical turbulent flux and the storage terms (\(F_{c}+F_{s}\)) were considerably smaller compared to independent estimates of nighttime ecosystem respiration as measured by chambers; (ii) during nighttime horizontal (\(F_{ha}\)) advection was an important term of Eq. (6); (iii) NEE calculated by taking into account all terms of Eq. (6) was similar to nighttime ecosystem respiration
estimated by the approach put forward by van Gorsel et al. (2007, 2008) and the chambers; (iv) different published methods for indirectly and directly accounting for advection resulted in a large divergence in the annual carbon balance; (v) accounting for advection generally turned the site from a sink to a source; and (vi) common approaches of filtering for periods of supposed advection (u* or \( \sigma_w \)) agreed with each other to within 20% during the growing season and increased the annual NEE by 1-70% depending on the method used (Table 1).

The latter point suggests the potential challenges (e.g. Vickers et al. 2012; van Gorsel et al. 2007; Kutsch et al. 2008), in selecting an objective threshold useful to exclude periods when advection dominates at our site. At Torgnon the constantly low u* values (0.01-0.1 ms\(^{-1}\)) during nighttime revealed that common atmospheric conditions (Fig. 2) are such that the site never reaches a turbulence regime which is high enough for CO\(_2\) gradients to vanish, finally explaining the lack of the relationship between u* and the fluxes (\( F_c + F_s \) and \( F_{ha} + F_{va} \)).

Despite our site being located in complex terrain, the observed steady atmospheric nocturnal pattern and the very constant bi-directional wind system enabled us to measure horizontal and vertical advection in a simplified 2D transect, with a reasonably low (9 and 20%) measurement error, as successfully accomplished at other mountain sites (Marcolla et al. 2005; Etzold et al. 2010). Since our measurements were conducted at two different locations but were temporally separated, our set-up did not allow to provide an accurate estimate of spatial uncertainty in advection measurements (e.g. Marcolla et al. 2014), however the small differences between measurements in the first and the second locations (Fig. 4, Fig. A.1) suggested that spatial representativity is a minor issue in this specific experiment.

Finally, the low and homogeneous canopy of the grassland had a large advantage compared to forest ecosystems, as we could also compare our estimation of the ACMB and other NEE correction methods with independent measurements of ecosystem respiration carried out at an appropriate temporal (half-hourly) and spatial (ecosystem) scale by automated respiration chambers. We are aware
that also the chamber method are prone to some errors (e.g. Riederer et al. 2014), but little and contrasting information exist on its potentials and pitfalls (Görres et al. 2015; Koskinen et al. 2014). Indeed, only few studies used automated chambers, especially on the whole ecosystem scale, and a standardised procedure for checking the quality of data as for EC still does not exist (Vargas et al., 2011). Riederer et al. (2014) concluded that depending on atmospheric conditions, during nighttime chambers are biased compared to EC. Based on a intercomparison campaign, Görres et al. (2015) demonstrated instead that the modern design and operation of automatic chambers has the potential of providing reliable nighttime CO$_2$ flux data. However, since the actual ecosystem CO$_2$ fluxes can never be known in environmental conditions, Görres et al. (2015) also concluded that it is not possible to test whether the LI-8100 nighttime measurements are overestimated or not. In the present study we showed that chamber measurements at our site agreed with EC-NEE when the latter is corrected using the R$_{\text{max}}$ approach or the quantification of the ACMB.

**Evaluation of correction methods**

Horizontal advection amounted to significant values during nighttime, up to 100% of uncorrected NEE, and accounting for advection in the CO$_2$ conservation equation increased NEE by a factor of two. We found that directly accounting for advection allowed agreement between NEE$_{\text{acmb}}$ and two of the other methods tested: R$_{\text{max}}$ and R$_{\text{cham}}$. Since direct advection measurements are not feasible for long time periods, a method to estimate and extrapolate advection data to years without advection measurements was tested and resulted in a high correspondence to both NEE$_{\text{acmb}}$, R$_{\text{max}}$ and R$_{\text{cham}}$. This correspondence relies on the systematic pattern of nighttime wind direction and turbulence intensity, which allowed to estimate $F_{\text{mod}}$ with a simple approach. However, in the estimation of the term $F_{\text{mod}}$ some assumptions were made, i.e. a constant relationship between NEE and advection in space and time, which is not possible to be verified with the current set-up. Indeed, with the available data these assumptions can only be supported by the small variability observed in Figure
4, which includes observations made in two different locations (Fig. A.1, A.2),
and the systematic accordance between the $F_{\text{mod}}$ and $R_{\text{max}}$ approaches through
years. The method introduced by van Gorsel et al. (2007) agreed with direct and
estimated advection methods and, as for $\text{NEE}_{acmb}$ and $\text{NEE}_{F\text{mod}}$ significantly
matched also $R_{\text{cham}}$. Being based on the assumption that there are different
temporal scales for the decline of the turbulent flux, the storage flux, and the
build up of advection (van Gorsel et al., 2007), this method captures values of
$F_c+F_s$ in a short period just after sunset when the turbulent flux is dominant
and the advection terms are still negligible. In this period (19.00 CET) $F_c+F_s$
can be considered as representative of the unbiased CO$_2$ efflux as demonstrated
by the comparison with $R_{\text{cham}}$ (Figs. 4, 6).

**Impacts on annual estimates**

We also tested our approach in years different from the experimental one
and evaluated the contribution of directly accounting for advection on the un-
certainty of the yearly CO$_2$ budget. $R_{\text{max}}$ and $\text{NEE}_{F\text{mod}}$ gave similar results in
terms of seasonal and annual sums, and consequently $R_{\text{max}}$ could be considered
a good indirect method for accounting of advection at our site. Nevertheless,
differences between $R_{\text{max}}$ and $\text{NEE}_{F\text{mod}}$ were found when looking at the sea-
sonal course of nighttime fluxes (Fig. 7). Indeed, $\text{NEE}_{F\text{mod}}$, being based on
direct measurement of NEE plus a percentage of unaccounted CO$_2$ flux, well
represented the short-term variation of respiration, as demonstrated by the com-
parison with the variation of flux pattern measured by chambers (Fig. 7). Since
$R_{\text{max}}$ is based on the rejection of a large fraction of data, requiring appropriate
replacement with an empirically derived ecosystem respiration model, together
with the filtering methods, it showed a dampened seasonal course which resulted
in a lower representativeness of the temporal variation of the fluxes (Fig. 8).
On the yearly time span, our results showed that the use of $\text{NEE}_{u*}$ led to a non
significant (< 1%) change in uncorrected NEE, conversely, $\text{NEE}_{\sigma w}$, $\text{NEE}_{u*50}$
and $\text{NEE}_{REF}$ moved the net carbon balance towards less negative values on
average by 68 gCm$^{-2}$y$^{-1}$, since these methods allowed the determination of a
higher threshold. The highest departures from annual uncorrected NEE were found using both $R_{max}$ and $\text{NEE}_{Fmod}$ which added to the former on average 168 and 183 gCm$^{-2}$y$^{-1}$ respectively. By increasing the CO$_2$ loss from the ecosystem on average by 155-169\% ($R_{max}$-$\text{NEE}_{Fmod}$), during all the years but 2011, the use of both $R_{max}$ or $\text{NEE}_{Fmod}$ turned the ecosystem from a weak sink to a weak source. Considering all the tested approaches, the mean annual carbon balance of this ecosystem could range from -108 (NEE) to 75 (NEE$_{Fmod}$) gCm$^{-2}$y$^{-1}$. Therefore, for such an ecosystem, close to carbon-neutral, accounting for advection may have a crucial impact on the definition of its source/sink role compared to stronger sinks, e.g. vigorously growing forests. Indeed, during an anomalously productive year (Galvagno et al., 2013) as 2011, the net balance remained negative, also when accounting for advection.

5. Conclusion

Lately, it appears that the interest in quantifying advection has decreased (but see e.g. Siebicke et al. 2012), probably reflecting the demanding experimental effort that such measurements require as well as the discouraging results obtained in some studies (Aubinet et al., 2010). However, the current practice of accounting for the supposed contribution of advection to nighttime CO$_2$ exchange (i.e. $u^*$-filtering) could prove problematic in complex mountainous sites when the nighttime turbulent regime is continuously low. Accounting for advection caused NEE at our grassland site to increase on average by 183 gCm$^{-2}$y$^{-1}$ and turned the site from a sink to a source. We advocate that continuing efforts need to be made towards quantifying the contribution of advection to NEE and to further develop approaches for diagnosing and, if possible, accounting for advective flux contributions. Recently, Campioli et al. (2016) evaluated the convergence between eddy-covariance and biometric methods in the quantification of the carbon budget of forests and found that the correspondence is poor for sites where the fluxes are lower, but that these discrepancies are not related to the inaccuracy of EC measurements and processing. Since all the
methods considered in this study have potential issues, future work will be also
directed towards a comparison with biomass and soil carbon inventories at the
site, which, given the simple ecosystem, could provide key details on the unac-
counted fluxes.

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ment Project and Fluxdata project of FLUXNET, with the support of CDIAC,
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Appendix A. Considerations on uncertainty

Field campaign measurements in different locations/periods

The 2012 experimental campaign was composed by two sequential periods,
from 31 July to 10 August and from 10 to 21 August, in which turbulent flux and
advection measurements were conducted in two different locations of the study
site (Figure 1). Figure A.1 shows the mean diurnal variation of all terms of Eq.
6, separately for the first and the second locations (and periods). Figure A.2
shows the comparison between measurements carried out with the permanent
(EC-1) and the experimental (EC-2) station in the two locations.
Chamber measurements variability

Respiration chambers sampled a small area, and differences between chambers can lead to uncertainty in the measurements, however, the CV quantified during the study period appears to be quite low (18% on average). Figure A.3 shows the observed variability in chamber measurements during the field campaign (2012) and the validation years (2010, 2014).

FLUXNET2015 derived uncertainty

The additional table A.1 reports growing season nighttime (a) and yearly (b) NEE filtered using different percentiles of $u^*$ thresholds as derived from the FLUXNET2015 dataset. The use of a very high $u^*$ threshold ($\text{NEE}_{u^*95}$) potentially lead to greater annual sums compared to uncorrected NEE, $\text{NEE}_{u^*50}$, $\text{NEE}_{u^*50}$ and $\text{NEE}_{\text{REF}}$, but overall the budgets still remained below the upper limit of the range obtained using $R_{\text{max}}$ or $\text{NEE}_{F\text{mod}}$. Moreover, it must be noticed that the FLUXNET2015 yearly data were filtered for the whole year, while yearly sums obtained with the other methods were corrected only for the snow-free period as described in section 2.6. Indeed, when considering the seasonal values in table A.1, the highest percentile showed a lower deviation from uncorrected NEE.

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Table 1: Growing season nighttime (R_g < 20 Wm^{-2}) sums of NEE (gCm^{-2}) computed with different correction approaches and derived from independent chamber measurements (R_{cham}) for two validation years: NEE, uncorrected fluxes, NEE_u*, u*-filtered data, NEE_{σw}, σw-filtered data, NEE_u*50 and NEE_{REF}, independent u*-filtered data derived from FLUXNET2015, R_{max} data modeled on the basis of maximum value of after-sunset F_c+F_s, NEE_{F_{mod}}, NEE computed including advection. For NEE_u*50 and NEE_{REF} the IQR is reported (i.e. the difference between NEE filtered using the 75th percentile and 25th percentile of u* thresholds). Growing season is referred to the period during which chamber data were available for a given year, i.e. 127 days in 2010 and 168 days in 2014.

<table>
<thead>
<tr>
<th>Year</th>
<th>NEE</th>
<th>NEE_{u*}</th>
<th>NEE_{σw}</th>
<th>NEE_u*50</th>
<th>NEE_{REF}</th>
<th>R_{max}</th>
<th>NEE_{F_{mod}}</th>
<th>R_{cham}</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>129</td>
<td>129</td>
<td>149</td>
<td>158 (32)</td>
<td>156 (32)</td>
<td>236</td>
<td>264</td>
<td>293</td>
</tr>
<tr>
<td>2014</td>
<td>208</td>
<td>204</td>
<td>239</td>
<td>252 (65)</td>
<td>246 (65)</td>
<td>362</td>
<td>409</td>
<td>406</td>
</tr>
</tbody>
</table>

Table 2: Annual sums of NEE (gCm^{-2}y^{-1}) computed with different correction approaches: NEE, uncorrected fluxes, NEE_{u*}, u*-filtered data, NEE_{σw}, σw-filtered data, NEE_u*50 and NEE_{REF}, independent u*-filtered data derived from FLUXNET2015, R_{max} data modeled on the basis of maximum value of after-sunset F_c+F_s, NEE_{F_{mod}}, NEE computed including advection. For NEE_u*50 and NEE_{REF} the IQR is reported (i.e. the difference between NEE filtered using the 75th percentile and 25th percentile of u* thresholds)

<table>
<thead>
<tr>
<th>Year</th>
<th>NEE</th>
<th>NEE_{u*}</th>
<th>NEE_{σw}</th>
<th>NEE_u*50</th>
<th>NEE_{REF}</th>
<th>R_{max}</th>
<th>NEE_{F_{mod}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>-58</td>
<td>-58</td>
<td>-34</td>
<td>2 (41)</td>
<td>15 (41)</td>
<td>81</td>
<td>92.5</td>
</tr>
<tr>
<td>2011</td>
<td>-236</td>
<td>-234</td>
<td>-191</td>
<td>-156 (73)</td>
<td>-151 (73)</td>
<td>-60</td>
<td>-51</td>
</tr>
<tr>
<td>2012</td>
<td>-23</td>
<td>-19</td>
<td>-1</td>
<td>47 (48)</td>
<td>54 (48)</td>
<td>145</td>
<td>147</td>
</tr>
<tr>
<td>2014</td>
<td>-116</td>
<td>-119</td>
<td>-80</td>
<td>-57 (69)</td>
<td>-48 (69)</td>
<td>74</td>
<td>112</td>
</tr>
<tr>
<td>Average</td>
<td>-108</td>
<td>-107</td>
<td>-76</td>
<td>-40 (58)</td>
<td>-32 (58)</td>
<td>60</td>
<td>75</td>
</tr>
</tbody>
</table>
Table A.1: FLUXNET2015 derived uncertainty. NEE filtered using different percentiles of $u^*$ thresholds for both the growing season nighttime (a) and the yearly (b) sums (gCm$^{-2}$) of NEE.

(a)

<table>
<thead>
<tr>
<th>Year</th>
<th>NEE$_{u*05}$</th>
<th>NEE$_{u*25}$</th>
<th>NEE$_{u*75}$</th>
<th>NEE$_{u*95}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>123</td>
<td>146</td>
<td>179</td>
<td>198</td>
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<tr>
<td>2014</td>
<td>162</td>
<td>206</td>
<td>272</td>
<td>296</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th>Year</th>
<th>NEE$_{u*05}$</th>
<th>NEE$_{u*25}$</th>
<th>NEE$_{u*75}$</th>
<th>NEE$_{u*95}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>-29</td>
<td>-6</td>
<td>35</td>
<td>60</td>
</tr>
<tr>
<td>2011</td>
<td>-224</td>
<td>-187</td>
<td>-114</td>
<td>-89</td>
</tr>
<tr>
<td>2012</td>
<td>20</td>
<td>34</td>
<td>82</td>
<td>100</td>
</tr>
<tr>
<td>2014</td>
<td>-139</td>
<td>-108</td>
<td>-38</td>
<td>-19</td>
</tr>
</tbody>
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Figures
Figure 1: The Torgnon study site. Colours represent altitude. The EC permanent (EC-1) and EC-2 experimental towers are marked. Arrows indicate location and orientation of the EC-2 transects. Right top figure shows the main wind pattern at the EC-1 site.
Figure 2: Median diurnal variation of a) wind direction (°), b) wind speed (ms$^{-1}$), c) global radiation (Wm$^{-2}$), d) Monin-Obukhov stability parameter (z/L), e) friction velocity u (ms$^{-1}$) during the 2012 field campaign (black solid line) and the whole study period (2010-2013, dark grey dashed line) with its variability range (10% and 90% inter quantile grey solid lines). The red line indicates the time of the day when calm conditions build up.
Figure 3: Wind and CO\textsubscript{2} profiles during the 2012 field campaign. Left panel: mean horizontal wind speed, \( u \) (ms\textsuperscript{-1}), at different heights above the ground, pooled by day (dashed line) and night (solid line) hours. Right panel: Mean CO\textsubscript{2} concentrations (ppm) at the same heights pooled by day (dashed line) and night (solid line) and by uphill (black) and downhill (red) measurement points.
Figure 4: Mean diurnal variation of measured vertical turbulent CO$_2$ flux plus the storage term $F_c+F_s$ (blue line), horizontal advection, $F_{ha}$ (yellow line), vertical advection $F_{va}$ (green line), the full mass balance $F_c+F_s+F_{ha}+F_{va}$ (black line), the storage term $F_s$ (grey line, right axis), and the CO$_2$ flux from automated chambers (red solid line is used for nighttime and red dashed line for daytime), during the 2012 field campaign (note that chambers were opaque, and thus did not measure any photosynthetic CO$_2$ uptake during daytime). Shaded areas represent for each method the combined temporal and spatial variability during the study period, expressed as 95% confidence intervals (i.e. CI, 1.96 times the standard error of the mean.)
Figure 5: Relationships of nighttime vertical turbulent flux plus the storage term $F_c+F_s$ (blue), horizontal advection $F_{ha}$ (orange) and vertical advection $F_{va}$ (green) to classes of friction velocity $u^*$, during the 2012 field campaign.
Figure 6: Distribution and mean of nighttime values of NEE computed with different correction methods: uncorrected NEE, u*-filtered NEE, σw-filtered NEE, independent u*-filtered data derived from FLUXNET2015, and NEE derived from NEEREF, data modeled on the basis of maximum value of after-sunset turbulent and storage terms, Rmax, NEE computed including advection, NEEPa, NEE computed including the estimated advection Fmod, NEEFmod, and records of chambers Rcham. Different letters indicate significant differences (p<0.05) between the investigated methods based on the Tukey HSD test. The dark line represents the mean, boxes extend to the 25th and 75th percentiles, whiskers represent 1.5 times the interquartile distance. Points lying beyond the extremes of the whiskers are represented by open circles.
Figure 7: Gap-filled time series of nighttime NEE computed with different correction approaches for two validation years (summer period), 2010 and 2014: uncorrected NEE (grey), u*-filtered NEE$_{u*}$ (cyan) and independent u*-filtered data derived from FLUXNET2015, NEE$_{u*50}$ and NEE$_{REF}$ (purple), $\sigma_w$-filtered NEE$_{\sigma_w}$ (blue), data modeled on the basis of maximum value of after-sunset turbulent and storage terms R$_{\text{max}}$ (green), NEE computed including the estimated advection F$_{mod}$, NEE$_{F_{mod}}$ (orange), and records of chambers R$_{\text{cham}}$ (red).
Figure 8: Taylor diagram presenting the relative skills with which each NEE calculation method matches chamber observations $R_{\text{cham}}$. The similarity between a given calculation approach and the chamber patterns is quantified by means of their correlation, the amplitude of their variations, i.e. their standard-deviation (represented by radial distance from the origin, black arc represents the reference $R_{\text{cham}}$ standard deviation) and their centered root mean square difference (grey contours). Data are relative to the summer period of the validation years 2010 and 2014.
Figure A. 1: Mean diurnal variation of all term of Eq. (6) measured in the two locations of Figure 1, during the first and the second period of the experimental campaign.
Figure A. 2: CO$_2$ turbulent flux measurements carried on with the permanent (EC-1) and the experimental station (EC-2) in the two locations. Red line represents $R_{Cham}$, the mean nocturnal respiration by chambers.
Figure A. 3: Nighttime time series of chambers CO$_2$ fluxes during the field campaign in 2012, and in 2010 and 2014. Black points represent the half-hourly mean between the chambers and the grey bars their standard deviations.