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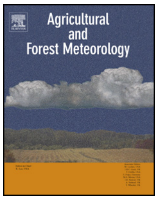

Contribution of advection to nighttime ecosystem respiration at a mountain grassland in complex terrain

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ABSTRACT

Net ecosystem carbon dioxide (CO_2) 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 CO_2 conservation equation increased NEE by a factor of two. NEE calculated by taking into account all terms (NEE_{acmb}), i.e. turbulent exchange, change in storage and advection of CO_2, matched the approach based on the after-sunset maximum in the vertical turbulent flux and change in the storage of CO_2 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 ($-108\ gCm^{-2}\ y^{-1}$) to a source ($75\ gCm^{-2}\ y^{-1}$) of CO_2.

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% to 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., 2005; Etzold et al., 2010; Foken et al., 2012). During stable and calm nighttime conditions, and in particular in complex terrain these requirements are however likely to be violated and the advective

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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 fullfilled. 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 statured 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 economical 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 CO_2 (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 CO_2 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 $m^2 m^{-2}$ 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 m, the site is characterized by undulating terrain with slopes at various angles and expositions (Fig. 1). Regular eddy covariance (EC) measurements of CO_2 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 CO_2 and H_2O 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 CO_2 concen-