Agricultural and Forest Meteorology 263 (2018) 287–291

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Attributing the energy imbalance by concurrent lysimeter and eddy covariance evapotranspiration measurements

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ARTICLE INFO

Keywords:
Energy balance closure
Eddy covariance
Bowen ratio
Evapotranspiration
Latent heat flux

ABSTRACT

The commonly observed lack of energy balance closure at eddy covariance flux tower sites represents an outstanding problem in micrometeorology and significantly compromises the value of eddy covariance latent and sensible heat flux measurements. Here we used concurrent lysimeter and eddy covariance evapotranspiration measurements to correct for the energy imbalance attributable to the eddy covariance latent heat flux measurements (32%) and then, by assuming that the Bowen ratio is correctly quantified by the eddy covariance method, attributed the remainder of the energy balance to the sensible heat flux (10%) and the available energy (58%). We discuss our findings with respect to the ongoing discussion on the causes of the energy imbalance and approaches to force energy balance closure.

1. Introduction

The general lack of energy balance closure at eddy covariance (EC) sites on the order of 20–30 % is a widespread and persistent problem in micrometeorology (Foken, 2008; Leuning et al., 2012; Stoy et al., 2013), which undermines the credibility of the eddy covariance method as a tool for determining the surface-atmosphere energy and mass exchange and the value of these data for calibrating and validating models.

Causes for the energy imbalance discussed in the literature include mismatches in footprint (between turbulent heat fluxes and available energy), measurement and calculation errors, neglect of advective heat fluxes, and inadequate sampling of low-frequency flux contributions (Foken, 2008; Leuning et al., 2012), but so far no consensus has been reached with regard to the relative importance of these factors. As a consequence, several, quite contrasting, approaches have been proposed in order to force energy balance closure (e.g. Charuchittipan et al., 2014; Twine et al., 2000; Wohlfahrt et al., 2009) and compared against each other using independent measurements of one of the energy balance components as a reference. To this end, up-scaled leaf transpiration (Wohlfahrt et al., 2010), tree sapflow (Perez-Priego et al., 2017) and in particular lysimeter measurements (Chávez et al., 2009; Ding et al., 2010; Gebler et al., 2015; Hirschi et al., 2017; Mauder et al., 2018), as well as process-based model simulations of evapotranspiration (Mauder et al., 2018) were used. While many closure approaches, including extreme ones (i.e. all missing energy attributed to a single energy balance term), have been tested (e.g. Knauer et al., 2018; Wohlfahrt et al., 2009), there are theoretical arguments in favour of forcing energy balance closure by attributing the energy imbalance to the latent and sensible heat flux so that the Bowen ratio remains unchanged (Foken, 2008).

Wohlfahrt and Widmoser (2013) introduced a simple framework for studying the energy imbalance (ε), i.e.

$$\varepsilon = A - H - LE \tag{1}$$

with A representing the available radiation (typically net radiation minus the soil heat flux minus other heat storage), H the sensible heat flux and LE the latent heat flux (all units: W m^{-2}). They proposed three dimensionless weights (w_A, w_H and w_L) for each term on the RHS of Eq. (1) which obey the following two constraints: (i) each weight is bound between zero and unity and (ii) the three weights sum up to unity. Provided these weights are known, the terms on the RHS of Eq. (1) can be corrected for the lack of energy balance closure as:

$$A_c = A - w_A\,\varepsilon \tag{2a}$$

$$H_c = H + w_H\,\varepsilon \tag{2b}$$

$$LE_c = LE + w_L\,\varepsilon \tag{2c}$$

Mathematically, there are infinite combinations of these three weights which equally well close the energy balance and thus additional information is required to meaningfully constrain the weights

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https://doi.org/10.1016/j.agrformet.2018.09.003
Received 23 March 2018; Received in revised form 27 August 2018; Accepted 4 September 2018

(Wohlfahrt and Widmoser, 2013).

The objective here is to extend the approach of Wohlfahrt and Widmoser (2013) by using independent evapotranspiration measurements by a lysimeter as a reference in order to (i) estimate the weight w_L for correcting for the fractional energy imbalance of the EC latent heat flux measurements and then (ii) estimate the remaining weights w_A and w_H by requiring that the Bowen ratio of the original measurements remains conserved.

2. Material and methods

The data used in this study were gathered at the hydro-meteorological station Rietholzbach, a grassland site situated in the foothills of the Alps in Switzerland (47.37 °N, 8.99 °E, 795 m a.s.l), by the Institute for Atmospheric and Climate Science, Swiss Federal Institute of Technology, Zürich (Seneviratne et al., 2012).

The measurements, processing and quality control of the data set used in this study have been described recently in great detail by Hirschi et al. (2017) with corrections in (Hirschi et al., 2018). Briefly, the EC measurements were conducted on a 9 m flux tower installed 12.5 m from of the lysimeter. It is equipped on three levels with sonic anemometers (CSAT3, Campbell Scientific, USA) and, on the bottom and the top level, with an open-path CO_2 and H_2O gas analyser (Li-7500, Li-Cor, USA). The data for this study were taken from the 2 m level. Data were acquired at a rate of 10 Hz by a data logger (CR3000, Campbell Scientific, USA) and processed to hourly fluxes following Aubinet et al. (2012). Post-processing included a coordinate rotation using the planar fit approach (Wilczak et al., 2001), a time lag correction by maximising the cross-correlation between the water vapour signal and the vertical wind speed (McMillen, 1988), spectral corrections (Moore, 1986), the conversion of buoyancy to sensible heat flux (Schotanus et al., 1983) and the correction for density effects (Webb et al., 1980). The large weighing lysimeter (3.1 m^2 surface area, total depth of 2.5 m) used in this study was installed in 1975 with local backfilled soil and is constructed to produce evaporation data with an accuracy of about 0.03 mm/h (approx. 20 W m^{-2}). The plant species composition on the lysimeter is similar to the one in the EC footprint and management (harvesting) also follows the practise applied to the EC footprint, except for that mineral fertiliser instead of slurry is applied (Hirschi et al., 2017). There is no installation to adjust the soil water content inside the lysimeter to the surrounding, which may cause lower evapotranspiration during dry periods. Eddy covariance and lysimeter latent heat flux measurements, the remaining components of the energy balance (i.e. A and H) and ancillary data (air temperature and vapour pressure, air pressure and the aerodynamic resistance) were available as hourly averages for the period May-October 2013.

Filtering data for 5 a.m. – 8 pm local time, 1600 complete data sets were available for further analysis. From these we removed 536 data sets during periods of (i) gusty winds affecting the lysimeter measurements, (ii) dewfall registered by the EC but not by the lysimeter measurements and (iii) precipitation affecting lysimeter readings. In addition, 144 EC data sets, mostly during morning and evening hours, were removed on the basis of the out-of-bound concept introduced by Wohlfahrt and Widmoser (2013). After the above data filtering, 920 data-sets remained for further processing.

3. Results

The average energy balance ratio $(LE + H)/A$ amounted to 0.81 ± 3.7, a regression of $LE + H$ as a function A ($R^2 = 0.95$) yielded a slope of 0.79 ± 0.01 and an offset of 11.8 ± 1.2 W m^{-2}. The average energy imbalance was negative (down to ca. −50 W m^{-2}) in the early morning and evening and peaked at values of 80 W m^{-2} during daytime (Fig. 1d). Average eddy covariance latent heat fluxes peaked at approx. 220 W m^{-2}, while the lysimeter latent heat flux measurements reached maxima of 240 W m^{-2} on average (Figs. 1a–b). The diurnal course of the difference between the two exhibited a bi-modal shape with minima in the early morning, late morning and evening, and maximum deviations around 8 a.m. and 3 pm (Fig. 1c). The noontime Bowen ratio (H/LE) amounted to 0.36, the evaporative fraction (LE/A) to 0.59.

At first sight, determining the weight w_L from the eddy covariance (LE_{EC}) and lysimeter (LE_{LY}) latent heat flux measurements individually for each hourly data set appears simple, i.e.

$$w_L = (LE_{LY} - LE_{EC})/(A - H - LE_{EC}) \tag{3}$$

Considering uncertainties of A, H and LE_{EC} of 12, 13 and 30 W m^{-2} (Alfieri et al., 2012) and 20 W m^{-2} for LE_{LY} and propagating these to w_L results in a range of -105 to 105, clearly violating our constraint of w_L to be between zero and unity. In fact, using the measured values resulted in an average w_L of 0.70 ± 36.4. We thus approached the determination of w_L by regressing the difference between lysimeter and EC latent heat fluxes as a function of the energy imbalance, i.e.

$$LE_{LY} - LE_{EC} = w_L\,\varepsilon + d \tag{4}$$

Here w_L represents the slope of the best-fit linear relationship and the y-intercept (d) may be interpreted as a systematic difference between lysimeter and EC latent heat flux measurements.

For all data pooled, w_L determined this way amounted to 0.25 ± 0.03 and the y-intercept to 3.0 ± 1.3 W m^{-2} (Fig. 2), the best-fit linear relationship however explained only a small fraction of the variability in LE_{LY}-LE_{EC} ($R^2 = 0.07$). Closer inspection of Fig. 2 indicates that stratifying the data by time of day may yield relationships with higher predictive power and we thus applied the regression to blocks of data filtered by time of day. The diurnal course of w_L largely mirrored the difference between lysimeter and EC latent heat fluxes (Fig. 1c) and accordingly w_L reached maximum values of 0.4 in the morning and evening with a dip in between and the lowest values in the early morning and late evening (Fig. 3). The y-offset varied between -7 and 15 W m^{-2} (data not shown). Filtering the data by other criteria yielded patterns, which could be explained by the diurnal variations of w_L and the filtering variable. Here we show the relationship between w_L and the magnitude of the latent heat flux as an example (Fig. 4), which reflects the bimodal diurnal pattern of the difference between lysimeter and EC latent heat fluxes (Fig. 1c) and the bell-shaped diurnal pattern of the latent flux (Fig. 1a).

With w_L and y-intercepts determined as described above, EC latent heat flux measurements can be corrected for the fractional energy imbalance by means of Eq. (4), as demonstrated, again for bin-averaged diurnal courses, in Fig. 5. Corrected EC latent heat fluxes exceeded the original ones on average by 8.5 W m^{-2}, with maximum average values of ca. 20 W m^{-2} in the late morning/noontime (Fig. 5), a result of the diurnal shapes of w_L and the energy imbalance (Fig. 1d). Corrected EC LE did not match lysimeter LE perfectly (Fig. 5), which is a consequence of the applied regression approach (Fig. 2, Eq. (4)). Maximum average absolute differences between lysimeter and corrected EC LE remained below 20 W m^{-2}, the accuracy of the lysimeter LE measurements.

After having determined w_L, the potential range of the two remaining weights, w_A and w_H, narrows down to between zero and 1-w_L, but without further information, neither w_A nor w_H can be determined.

One constraint for determining w_H can be derived from the proposal by Twine et al. (2000) that any energy balance closure operation should maintain the Bowen ratio, i.e. H/LE, of the original EC flux measurements, a proposal which is supported by theoretical arguments (Foken, 2008). That means, w_H in Eq. (2b) is chosen as to satisfy $H_c/LE_c = H/LE$. Once this is accomplished, w_A follows as 1-w_L-w_H. The results of this attempt to further narrow down w_H and w_A are shown in Fig. 3a. The weight w_H was around 0.05 during the early morning, reached maximum values of 0.15 around mid-morning and then decreased almost linearly to very small values in the evening (Fig. 3a). The weight w_A, accordingly, exhibited values close to 0.8 in the morning and evening and varied between 0.5 and 0.6 during most of the daytime hours (Fig. 3). Averaged over the time period 8 a.m. to 6 pm, the weights w_L,