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Evaluation of eddy covariance latent heat fluxes with independent lysimeter and sapflow estimates in a Mediterranean savannah ecosystem

Oscar Perez-Priego[a,*], Tarek S. El-Madany[a], Mirco Migliavacca[a], Andrew S. Kowalski[b], Martin Jung[a], Arnaud Carrara[c], Olaf Kolle[a], M. Pilar Martín[d], Javier Pacheco-Labrador[d], Gerardo Moreno[e], Markus Reichstein[a]

[a] Max Planck Institute for Biogeochemistry, Jena, Germany
[b] Departamento de Física Aplicada, Universidad de Granada, Granada, Spain
[c] Fundación Centro de Estudios Ambientales del Mediterráneo (CEAM), Valencia, Spain
[d] Environmental Remote Sensing and Spectroscopy Laboratory (SpecLab), Institute of Economics, Geography and Demography (IEGD-CCHS), Spanish National Research Council (CSIC), Spain
[e] Forest Research Group, Universidad de Extremadura, Plasencia, Spain

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ABSTRACT

We evaluated the underlying causes of differences between latent heat (LE) fluxes measured with two enclosed-path eddy covariance systems (EC) at two measurement levels and independent estimates in an open oak-tree grass savannah over almost one year. Estimates of LE of the well-stablished underlying grass by replicated weighable tension-controlled lysimiters (LE_{Lys}) provided a robust baseline against which to compare EC LE measured at 1.6 m above ground ($LE_{\text{-}1.6}$). Similarly and at the ecosystem level, LE up-scaled using independent measurements ($LE_{upscaled}$ = sap flow + lysimeter) was benchmarked with 3 EC-derived LE estimates: 1) LE measured by a EC tower at 15 m above ground ($LE_{\text{-}15}$), 2) $LE_{\text{-}15}$ adjusted to close the energy balance by using the Bowen ratio method ($LE_{Bowen} = (R_n - G)/(1 + \beta)$), and 3) LE derived from the energy budget residual ($LE_{residual} = R_n - G - H_{\text{-}15}$). The sensitivity of EC LE to the correction method applied (i.e. corrections for low-pass filtering effects on water vapor fluctuations and the so-called angle-of-attack correction) and its impact on the energy balance closure (EBC) were also evaluated.

Comparison of EC LE between 1.6 m- and 15 m-heights showed that grass dominated annual evaporative loss from 69 to 87% depending upon the spectral correction method applied. Results revealed substantial underestimation of $LE_{\text{-}1.6}$ (up to 35%) compared to LE_{Lys}, which mostly occurred during the growing season. However those differences were remarkably lower when likening $LE_{\text{-}15}$ versus $LE_{upscaled}$ (14%) suggesting that the dampening of the water vapor fluctuations due to low-pass filtering effects is more pronounced near the surface. Interestingly, a diagnostic evaluation of the errors with a random forest model showed that differences followed quite structured patterns and were associated with certain atmospheric conditions: turbulent mixing deficiencies and or stable atmospheric stratification. In addition, the model showed that differences increased with increasing relative humidity (RH) and soil moisture. Our results revealed that the degree of EBC is highly sensitive to the flux correction method applied, in particular when correcting for flow distortion effects. Typically, turbulent fluxes fell below the measured available energy (slope 0.92) but the slope switched abruptly when the angle-of-attack correction was applied (slope 1.07). Consistent with the EBC, independent LE estimates matched well with LE_{Bowen} and the EBC gap decreased when $LE_{upscaled}$ was used (slope 0.96). The use of independent estimates of LE together with machine learning methods are proposed as a powerful means to diagnose the complexity behind LE errors and give insights into the energy imbalance problem. In addition to inherent randomness of EC LE data, accounting for uncertainties associated with the appropriateness of the correction method applied is highly recommended.

* Corresponding author at: Biosphere-Atmosphere Interactions and Experimentation Group, Biogeochemical Integration Department, Max Planck Institute for Biogeochemistry, Jena, Germany.
E-mail addresses: opriego@bgc-jena.mpg.de, oscarperezpriego@gmail.com (O. Perez-Priego).

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Nomenclature

A_{trunk}	The average cross sectional area of sapwood for trees within the half-hourly determined tower footprint
EC	Eddy covariance
ϵ	The relative error in EC LE, error estimated as indicated below: $\epsilon_{1.6\_M}$ calculated as $(LE_{Lys} - LE_{\_1.6\_M})/LE_{Lys}$; $\epsilon_{1.6\_F}$ calculated as $(LE_{Lys} - LE_{\_1.6\_F})/LE_{Lys}$; ϵ_{15_M} calculated as $(LE_{upscaled} - LE_{\_15\_M})/LE_{upscaled}$; ϵ_{15_I} calculated as $(LE_{upscaled} - LE_{\_15\_I})/LE_{upscaled}$
$H_{\_15}$	The sensible heat flux measured by the EC tower 15 m above ground
LE_{Bowen}	Estimated latent heat as $R_n - G/(1+\beta)$, where β is the Bowen ratio calculated as $H_{\_15}/LE_{\_15\_M}$
$LE_{\_1.6}$	Latent heat measured by the 1.6 m EC tower: $LE_{\_1.6\_M}$, including the spectral correction of Moncrieff et al. (1997); $LE_{\_1.6\_F}$, including the spectral correction of Fratini et al. (2012); $LE_{\_1.6\_filter}$, gap-filled $LE_{\_1.6\_F}$ when $\epsilon_{1.6\text{-}F} > 30\%$
$LE_{\_15}$	Latent heat measured by the 15 m EC tower: $LE_{\_15\text{-}M}$ including the spectral correction of Moncrieff et al. (1997); $LE_{\_15\text{-}I}$, including the spectral correction of Ibrom et al. (2007); $LE_{\_15\text{-}I\_N}$, including the spectral correction of Ibrom et al. (2007) and angle-of-attack correction (Nakai et al., 2006); $LE_{\_15\text{-}I\_filter}$, gap-filled $LE_{\_15\text{-}I}$ when $\epsilon_{15\_F} > 30\%$
LE_{Lys}	Latent heat exchange by the understory layer from replicated lysimeters (n = 6)
$LE_{residuals}$	Latent heat exchange determined from the energy budget residual $(R_n - G - H_{\_15})$
LE_{RF}	Modelled latent heat exchange via RF
LE_{sap}	Estimated stand transpiration and expressed in energy terms ($W\,m^{-2}$)
$LE_{upscaled}$	Estimated LE via aggregation of LE_{Lys} and LE_{sap}
$LE_{ensemble}$	Estimates computed with an ensemble of $LE_{\_15\_M}$, $LE_{\_15\_I}$, $LE_{\_15\_I\_N}$, $LE_{residuals}$, LE_{Bowen}
RF	The random forest model
RH	Air relative humidity
θ_s	Scaled soil water content at 10 cm depth ($\theta_s = SWC/SWC_{max}$)
$Td_{footprint}$	Is the tree density in the footprint area
u.	The friction velocity
z/L	Monin–Obukhov dimensionless stability parameter

1. Introduction

The main causes for the observed lack of energy surface balance closure – the mismatch between turbulent energy fluxes (latent heat, LE, and sensible heat, H) and the available energy (net radiation, (R_n) ground heat flux (G) and changes in heat storage) – are currently under debate (e.g. Foken et al., 2011). This inconsistency casts doubt on the accuracy of eddy covariance (EC) data and further evaluation of measurement errors using independent methods is highly desirable (Mamadou et al., 2016; Soubie et al., 2016). Among micrometeorological methods, EC is widely used in global long-term observation networks such as FLUXNET (Baldocchi et al., 2001), and provides measurements of both LE and H, as well as other trace gas fluxes (e.g. CO_2, and CH_4) over plant canopies. During recent decades, many studies have analyzed the observed gap in the energy balance closure (EBC) across sites with contrasted characteristics and environmental conditions (Barr et al., 2006; Foken et al., 2010; Franssen et al., 2010; Lee and Black, 1993; Moderow et al., 2009; Oncley et al., 2007; Stoy et al., 2006; Wilson et al., 2002). Such studies have shown that the sum of EC-derived H and LE systematically falls below the measured available energy.

Reasonable efforts have been made to study the underlying errors of turbulent fluxes that might explain such inconsistencies (Foken et al., 2011). On one hand, mismatches between radiometric and turbulent flux footprints or errors in available energy estimates have been shown to be minor (<10%) compared to the widely observed gap (10–30%; Stoy et al., 2013) and cannot fully explain the lack of EBC (Foken et al., 2010; Twine et al., 2000). Therefore, factors related to the processing steps of EC flux calculation and corrections, turbulence statistics, atmospheric stability, storage, advection and other issues related to instrumental set up, and site characteristics have been identified as possible causes of bias in EC data (Aubinet et al., 2000; Finnigan et al., 2003; Foken et al., 2006; Horst et al., 2015; Leuning et al., 2012; Mamadou et al., 2016; Mauder et al., 2010; Mauder and Foken, 2005; Van Der Molen et al., 2004). For example, the lack of EBC has been shown to be modest under highly turbulent conditions, but increases markedly when turbulence is limited (Amiro, 2009; Barr et al., 2006; Chávez et al., 2009; Franssen et al., 2010; Oliphant et al., 2004; Stoy et al., 2013; Wilson et al., 2002). This suggests that the role of the friction velocity (u_*) or stability parameters should not be only considered for screening nocturnal CO_2 turbulent exchange errors but also for EC-derived H and LE as well (Stoy et al., 2006). Further causes of bias in EC data have been associated with measurement errors of vertical wind velocity due to flow distortion effects by non-orthogonal anemometer types (e.g. Gill type), which might result in inaccurate measurements of H and LE (Van Der Molen et al., 2004). Also, it has been shown that discrepancies in the EBC are reduced by applying the so-called angle-of-attack correction (Frank et al., 2013; Horst et al., 2015; Kochendorfer et al., 2012; Nakai et al., 2006). However, some concerns have been raised regarding this correction and it remains a matter of debate (Mauder, 2013; Kochendorfer et al., 2013). These facts, among others (e.g, the storage term; Leuning et al., 2012), highlight important uncertainties, particularly when EC data are widely used to evaluate or parameterize terrestrial biosphere or hydrological models, or to derive ecosystem functional properties such as water use efficiency or evaporative fraction, that assume complete EBC (Jaeger and Kessler, 1997). One open question is the degree to which the energy balance residual can be i) equally attributed to measurement errors in LE and H, or mostly assigned to either ii) LE or iii) H (e.g. Wohlfahrt et al., 2009).

Presumably, option ii) might prevail if we consider the loss of high frequency eddies, which may cause underestimation of LE of up to 10% of the annual values (Wilson et al., 2000). Attenuation of water vapor fluctuations is well recognized in closed path EC systems (Fratini et al., 2012; Ibrom et al., 2007; Mammarella et al., 2009; Massman, 2000; Runkle et al., 2012) and can reduce the EBC by up to 19% (Su et al., 2004). Spectral analysis provides a means to check the quality of EC LE (Baldocchi and Meyers, 1991). Different analytical and empirical spectral correction methods have been proposed to correct for the attenuation of the true water vapor flux (Fratini et al., 2012; Horst, 1997; Ibrom et al., 2007; Moncrieff et al., 1997). Although the strengths and weakness among methods have been discussed (Massman and Lee, 2002), we lack quantitative comparison among methods (Su et al., 2004). Whilst all correction methods are prone to biases (Massman and Lee, 2002), inconsistencies in EC LE are often observed when comparing with independent approaches or models (Allen et al., 2011; Meiresonne et al., 2003; Twine et al., 2000; Wohlfahrt et al., 2010), and derivations of LE from the energy balance equation via either the residual ($LE_{residual} = R_n\text{-}G\text{-}H$) or the Bowen ratio [$LE_{Bowen} = R_n - G/(1+\beta)$] have been applied (Amiro, 2009; Castellví and Snyder, 2010; Chávez et al., 2009; Falge et al., 2005; Garratt, 1984; Twine et al., 2000;