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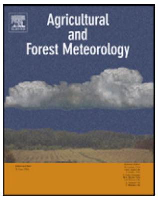

Energy balance closure of eddy-covariance data: A multisite analysis for European FLUXNET stations

H.J. Hendricks Franssen[a,b,c,*], R. Stöckli[d], I. Lehner[a], E. Rotenberg[e], S.I. Seneviratne[a]

[a] Institute of Atmospheric and Climatic Sciences, ETH Zurich, 8092 Zurich, Switzerland
[b] Institute of Environmental Engineering, ETH Zurich, 8093 Zurich, Switzerland
[c] Agrosphere, ICG-4, Forschungszentrum Jülich GmbH, Leo Brandtstrasse, 52425 Jülich, Germany
[d] Meteoswiss, Climate Services, Climate Analysis, Krähbühlstrasse 58, 8044 Zurich, Switzerland
[e] Department of Environmental Sciences and Energy Research (ESER), The Weizmann Institute of Sciences, Rehovot 76100, Israel

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ABSTRACT

This paper presents a multi-site (>20) analysis of the relative and absolute energy balance (EB) closure at European FLUXNET sites, as a function of the stability parameter ξ, the friction velocity u_*, thermally-induced turbulence, and the time of the day. A focus of the analysis is the magnitude of EB deficits for very unstable conditions. A univariate analysis of the relative EB deficit as function of ξ alone (both for individual sites and a synthesis for all sites), reveals that the relative EB deficit is larger for very unstable conditions ($\xi < -1.0$) than for less unstable conditions ($-0.02 > \xi \geq -1.0$). A bivariate analysis of the relative EB deficit as function of both ξ and u_*, however, indicates that for situations with comparable u_* the closure is better for very unstable conditions than for less unstable conditions. Our results suggest that the poorer closure for very unstable conditions identified from the univariate analysis is due to reduced u_* under these conditions. In addition, we identify that the conditions characterized by smallest relative EB deficits (elevated overall turbulence, mostly during day time) correspond to cases with the largest absolute EB deficits. Thus, the total EB deficit at the sites is induced mostly under these conditions, which is particularly relevant for evapotranspiration estimates. Further, situations with the largest relative EB deficits are generally characterized by small absolute EB deficits. We also find that the relative EB deficit does generally not correspond to the regression line of absolute EB deficit with the net radiation because there is a (positive or negative) offset. This can be understood from theoretical considerations. Finally, we find that storage effects explain a considerable fraction of the large *relative* (but small absolute) nocturnal EB deficits, and only a limited fraction of the overall relative and absolute EB deficits.

1. Introduction

Eddy-covariance (EC) flux measurements allow the assessment of land–atmosphere fluxes (e.g., carbon, water, and energy). They are now collected at several sites across the world as part of the FLUXNET network (e.g. Baldocchi et al., 2001). These data are essential for the estimation of the terrestrial water, energy and carbon balances, and for the understanding of the related physical and biological processes. This is of key relevance given the role of land surface processes for the climate system (e.g., Koster et al., 2004; Seneviratne et al., 2006; Friedlingstein et al., 2006). EC data are particularly useful for validating ecosystem, land-surface and climate models (e.g., Baldocchi and Wilson, 2001; Stöckli et al., 2008; Jaeger et al., 2009).

However, EC data are subject to important random errors (e.g., Richardson et al., 2006, 2008), problems like footprint heterogeneity (i.e., the turbulent fluxes show a strong spatial variation around the measurement tower; e.g., Göckede et al., 2008; Vanderborght et al., 2010), incomplete time series because some of the measured turbulent fluxes are excluded when deemed unreliable (e.g., Falge et al., 2001; Schmid et al., 2003), and especially, the systematic error related to the energy balance (EB) closure problem (e.g., Twine et al., 2000; Finnigan et al., 2003; Meyers and Hollinger, 2004; Barr et al., 2006; Foken, 2008). This latter issue is the main focus of the present study.

Several hypotheses underlie the estimation of turbulent fluxes from EC data: (1) the ergodic hypothesis (i.e., the time average converges over an appropriate time interval to the ensemble average); (2) the Taylor hypothesis (i.e., the temporal average replaces the spatial average); (3) statistical stationarity for the period under

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* Corresponding author at: Agrosphere, ICG-4, Forschungszentrum Jülich GmbH, Leo Brandtstrasse, 52425 Jülich, Germany. Tel.: +49 2461614462.
E-mail address: h.hendricks-franssen@fz-juelich.de (H.J.H. Franssen).

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consideration (i.e., the mean flux should not change significantly over the averaging time used to determine the mean); (4) horizontal homogeneity; and (5) the assumption that the average vertical wind component is equal to zero. The vertical sensible and latent heat flux densities are evaluated by the EC method according to:

$$Q_{\mathrm{H}} \equiv \rho c_{\mathrm{p}} \overline{w'\theta'} \tag{1}$$

$$Q_{\mathrm{E}} \equiv \rho l_{\mathrm{v}} \overline{w'q'}, \tag{2}$$

where Q_{H} is the sensible heat flux density ($\mathrm{W\,m^{-2}}$), Q_{E} the latent heat flux density ($\mathrm{W\,m^{-2}}$), ρ the air density ($\mathrm{kg\,m^{-3}}$), c_{p} the specific heat of moist air at constant pressure ($\mathrm{J\,kg^{-1}\,K^{-1}}$), w the vertical wind velocity ($\mathrm{m\,s^{-1}}$), θ the potential temperature (K), l_{v} the latent heat of vaporization ($\mathrm{J\,kg^{-1}}$), and q the specific humidity (kg water vapor/kg air). An overbar denotes averaging over time and a prime denotes a fluctuation from the mean.

Eqs. (1) and (2) are often evaluated for high-resolution (e.g., 10 Hz or 20 Hz) EC data. In most cases, the energy flux densities estimated on the basis of EC data (the sum of sensible and latent heat flux densities) over 30-min periods, do not sum up to net radiation together with measured soil heat flux density and heat storage. The evaluation of EC data over longer time periods often leads to a better closure (e.g., Jarvis et al., 1997). For half-hourly values, Wilson et al. (2002) report an average EB deficit of 21% over 22 FLUXNET sites, and Barr et al. (2006) report for three mature boreal forest stands in Canada EB deficits between 11% and 15%.

The exact factors leading to EB deficits are still debated. Neglecting heat storage in soil and canopy, as well as measurement errors have been suggested to have a substantial impact on the EB closure. However, increasing measurement precision for net radiation and soil heat flux density makes it less likely that measurement errors in these components are the main causes of the energy balance deficit (e.g., Foken, 2008). Another explanation that has been put forward in recent years, is that the EB closure problem may be related to low frequency turbulence that is not included in Eqs. (1) and (2), principally because the period over which the averages are calculated is relatively short (e.g., Finnigan et al., 2003; Foken et al., 2006). Indeed, coherent structures that are “attached” to the landscape may develop and these are not sampled with the EC method (e.g., Inagaki et al., 2006). This may be induced by e.g. land surface heterogeneities generating eddies at larger scales than those captured by the standard application of the EC method (e.g. Kanda et al., 2004; Inagaki et al., 2006; Mauder et al., 2007; Huang et al., 2009).

Previous studies based on experimental data suggested that the relative EB closure improves for increasing friction velocities u_* and increasing instability (e.g., Wilson et al., 2002; Barr et al., 2006). Under unstable conditions, convection is not suppressed and many studies find that the EC technique results in smaller relative EB deficits (e.g., Wilson et al., 2002; Barr et al., 2006). Also large u_* reduces the relative EB closure problem (e.g., Wilson et al., 2002; Barr et al., 2006), because the ergodic hypothesis and Taylor hypothesis are better fulfilled. However, under very unstable conditions also more low frequency turbulence (i.e., larger eddies) may be generated, for instance due to the occurrence of organized convection, meso-scale circulation systems or the development of deeper boundary layers (e.g., Finnigan et al., 2003). As mentioned, this may lead to a worsening of the EB closure for these conditions.

Indeed, from Figs. 4 and 5 in Barr et al. (2006) it can be seen that the relative EB closure is poorer for very unstable conditions than for less unstable conditions, although this result is not discussed in detail. Also Tanaka et al. (2008) find a larger relative EB deficit for very unstable conditions. Finnigan et al. (2003) hypothesize that a poorer relative EB closure induced by low frequency turbulence (related with large-scale convection), is expected to affect forested sites (high sensors) more than agricultural lands (low sensors).

In order to derive firmer conclusions concerning the EB closure under very unstable conditions, it is necessary to expand these results with a multi-site analysis. In the present study, we investigate EC data from up to 26 European FLUXNET sites, with a focus on the following questions:

(1) Is the larger relative EB deficit reported in the literature for very unstable conditions (compared with less unstable conditions) robust when analysed for a large number of sites?
(2) What are the relative contributions of mechanically- vs. thermally-induced turbulence for relative EB deficits under very unstable conditions?
(3) Does a multi-site analysis of the relative EB deficit as function of three or four variables (atmospheric stability ξ, u_*, thermal turbulence, time of the day) provide new insights regarding the relation between relative EB deficit and environmental factors?
(4) How does the *absolute* EB deficit relate with the *relative* EB deficit under different atmospheric conditions?
(5) How can cases with particularly poor EB closure be interpreted? Are such cases concomitant with conditions of small absolute net radiation?

Details on data and methods are provided in the next section, the results and analyses are presented in Section 3, and the main conclusions of this study are highlighted in Section 4.

2. Data and methods

2.1. Data

Flux tower data from 26 European FLUXNET sites, of which 21 forested sites, are analyzed here for the years 1997–2006 (Table 1). For some analyses the total number of considered sites is smaller when data was unavailable for given variables (e.g. no ξ data at Flakaliden and no u_* data at Bayreuth and Flakaliden, and missing storage data at many of the sites). The time series at the considered sites include at least two years with net radiation, turbulent flux densities and soil heat flux density. The turbulent fluxes for the European FLUXNET sites are estimated on the basis of 30-min averages. Table 1 provides more information about the sites. For further details, we refer the reader to the respective publications and references therein, or to the official FLUXNET homepage (http://www.fluxnet.ornl.gov).

The data were extracted from the common database and underwent a pre-screening. For this study, additional checks were made and for some sites erroneous radiation measurements were eliminated from the analysis. If for a given 30-min period net radiation, latent and sensible heat flux densities, soil heat flux density and storage terms are available, the energy balance deficit can be expressed as follows:

$$\Delta\mathrm{EB} = R_{\mathrm{n}} - Q_{\mathrm{H}} - Q_{\mathrm{E}} - Q_{\mathrm{G}} - \Delta S_{\mathrm{LE}} - \Delta S_{\mathrm{H}} - \Delta S_{\mathrm{BIO}} - \Delta S_{\mathrm{G}}, \tag{3}$$

where ΔEB is the absolute EB deficit ($\mathrm{W\,m^{-2}}$), R_{n} the net radiation ($\mathrm{W\,m^{-2}}$), Q_{G} the soil heat flux density ($\mathrm{W\,m^{-2}}$), and ΔS energy storage ($\mathrm{W\,m^{-2}}$) as latent heat between the soil surface and the EC sensors (hereinafter: in the canopy air space) (ΔS_{LE}), as sensible heat in the canopy air space (ΔS_{H}), in the biomass (ΔS_{BIO}) and in the soil layer between the heat flux plate and the soil surface (ΔS_{G}). The relative EB deficit is the absolute EB deficit standardized by R_{n}. In Section 2.2 details are provided on the calculation of the relative EB deficit.

In this study the energy storage terms are generally not considered in the analysis, because these data are only available for a limited number of sites, and in case of ΔS_{G} for none of the sites. However, the contribution of heat storage to the half-hourly energy