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Can an energy balance model provide additional constraints on how to close the energy imbalance?

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ABSTRACT

Elucidating the causes for the energy imbalance, i.e. the phenomenon that eddy covariance latent and sensible heat fluxes fall short of available energy, is an outstanding problem in micrometeorology. This paper tests the hypothesis that the full energy balance, through incorporation of additional independent measurements which determine the driving forces of and resistances to energy transfer, provides further insights into the causes of the energy imbalance and additional constraints on energy balance closure options. Eddy covariance and auxiliary data from three different biomes were used to test five contrasting closure scenarios. The main result of our study is that except for nighttime, when fluxes were low and noisy, the full energy balance generally did not contain enough information to allow further insights into the causes of the imbalance and to constrain energy balance closure options. Up to four out of the five tested closure scenarios performed similarly and in up to 53% of all cases all of the tested closure scenarios resulted in plausible energy balance values. Our approach may though provide a sensible consistency check for eddy covariance energy flux measurements.

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1. Introduction

The lack of energy balance closure, that is the sum of latent (λE) and sensible (H) heat exchange falling short of available energy (A), is a widespread problem of contemporary eddy covariance flux measurements. Available energy equals net radiation (R_N) minus the soil heat flux (G) and any other energy storage. At the majority of eddy covariance flux sites it is the rule rather than the exception to find that, on a half-hourly basis, $\lambda E + H$ underestimate A by 20–30% (Leuning et al., 2012; Wilson et al., 2002).

Given the significance of this apparently systematic bias, the energy balance closure has been studied extensively (see recent reviews by Foken, 2008; Foken et al., 2011; Leuning et al., 2012). Potential causes for the imbalance discussed in literature can be broadly categorized into four groups:

(1) *Mismatch in footprint*: Turbulent flux measurements of $\lambda E + H$ typically have footprints on the order of several hundreds of meters, while the footprint of R_N and G is typically on the order of tenth of meters to meters. While these differences in footprint, in particular at heterogeneous sites, may cause systematic differences between A and $\lambda E + H$, it is however unlikely that these differences would lead to a systematic overestimation of A and underestimation of $\lambda E + H$ at the majority of sites (Foken, 2008).

(2) *Measurement/calculation errors*: While there is variability between different models of net radiometers of different manufacturers, a recent review by Leuning et al. (2012) arrives at the conclusion that these differences are not able to account for the observed systematic differences between A and $\lambda E + H$. In contrast, Leuning et al. (2012), suggest that neglecting parts of the heat storage accounts for an appreciable fraction of the observed energy imbalance. Comparing half-hourly and daily averaged, when changes in heat storage should cancel, energy balance closures, the energy imbalance improved from an underestimation of 25% to 10%. Similarly, better energy balance closure has been reported for improved methods of soil heat flux calculation (Heusinkveld et al., 2004), heat storage in biomass (Lindroth et al., 2010) and taking into account the energy stored in metabolic processes (Jacobs et al., 2008). Errors in the vertical wind component due to sonic anemometer design (Kochendorfer et al., 2012; Nakai and Shimoyama, 2012) or contamination by horizontal velocity components (Leuning et al., 2012) have been shown to cause an underestimation of sensible and latent heat flux measurements. A systematic underestimation of latent and sensible heat fluxes also occurs if not corrected for effects of low- and high-pass filtering or density fluctuations (Leuning et al., 2012; Massman, 2000; Mauder and Foken, 2006).

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(3) *Advective flux divergence*: Horizontal and vertical advective flux divergence, neglected at most eddy covariance flux sites, may contribute to the energy imbalance, although Leuning et al. (2012) have shown that unrealistically large horizontal and/or vertical temperature and moisture gradients need to be invoked in order to explain typical midday energy imbalances of >100 J m^{-2} s^{-1}. It also should be noted that any advective flux divergence may cause a net import and/or export of energy (Finnigan, 1999), and it is thus again difficult to explain the observed systematic underestimation of $\lambda E + H$ with respect to A (Leuning et al., 2012).

(4) *Inadequate sampling of low frequency/large scale turbulent motions*: Turbulent transport at larger spatial/longer temporal scales not captured by typical half-hourly averaging times at a single tower have been shown to cause a systematic underestimation of sensible and latent heat fluxes on the order of 30% (Finnigan et al., 2003; Leuning et al., 2012; Mauder and Foken, 2006). These findings are corroborated by large eddy simulations (Kanda et al., 2004), spatially distributed eddy covariance measurements (Mauder et al., 2008) and area-averaging flux measurement methods such as scintillometry (Beyrich et al., 2006). Over short vegetation, however, underestimation of low frequency flux contributions appears to represent a minor issue (Foken et al., 2011).

In summary, past research has identified several potential causes for $A \neq \lambda E + H$, some of which also explain the systematic underestimation of $\lambda E + H$ with respect to A. Given the vast variability between sites in the factors that have the potential to contribute to the energy imbalance, such as measurement equipment and deployment, data post-processing, site topography and heterogeneity, ecosystem structure and so forth, it is however likely that no single cause is able to universally explain the imbalance.

The energy imbalance, on one hand, represents a theoretical problem as it violates the law of energy conservation. There are however also practical aspects to this problem which greatly limit the usefulness of eddy covariance energy flux measurements: The residual energy, $\varepsilon = A - (\lambda E + H)$, causes problems when using the measured energy balance components to calibrate/validate models that are based on the law of energy conservation, i.e. implicitly assume the energy balance to be closed (Williams et al., 2009). For example, Wohlfahrt et al. (2009) noted that widely varying estimates for the surface conductance to water vapor were obtained by inverting the Penman–Monteith combination equation depending on how ε was dealt with. A similar problem arises when measured evapotranspiration rates (i.e. the latent heat flux divided by the latent heat of vaporization) are used as input to a water budget model (e.g. Williams et al., 2012). In the simplest case such a water budget model would assume that precipitation (P) is consumed by evapotranspiration (ET) and runoff (R), i.e. $P = ET + R$, and it is clear that for a given P any errors in ET will propagate into R estimates. It should be mentioned that if ε is to be attributed to errors in λE and/or H, other scalar fluxes measured with the eddy covariance technique, e.g. carbon dioxide fluxes (Baldocchi, 2008), are likely to be underestimated as well.

For applications that require a closed energy balance, it may thus be desirable to force energy balance closure, i.e. attribute the residual energy to A, λE, H or combinations thereof. However, since a general solution to the 'energy balance problem' remains elusive, there is no generally accepted approach for doing so. Twine et al. (2000) suggested adjusting both λE and H according to the average energy imbalance. This approach, which was employed recently in a global analysis of evapotranspiration (Jung et al., 2010), conserves the Bowen-ratio (β) and closes the energy balance on average, however results in a (small) residual ε on the half-hourly time step. Wohlfahrt et al. (2009, 2010) additionally explored forcing energy balance closure by adjusting H, λE and A separately and by adjusting H and λE every half-hour so that β remains unchanged. However, even when independently measured evapotranspiration estimates were available, none of these closure options did clearly outperform the others (Wohlfahrt et al., 2010). Note that with models that assume a closed energy balance, using the energy balance components as measured may equate to unintentionally forcing energy balance closure. For example, Wohlfahrt et al. (2009) demonstrated that using the Penman–Monteith combination equation expressed in terms of A and λE amounts to implicitly allocating ε to H, while if it is expressed in terms of β the residual is distributed to H and λE in proportion to β.

So far, at least to the best of our knowledge, no attempt has been made to investigate whether additional constraints allow further insights into how to best force energy balance closure and thus in turn shed light on the causes underlying the energy imbalance. A logical starting point for doing so is to use the full energy balance, as detailed in the next section, to investigate the biological/physical plausibility of various closure options. With "full energy balance" we mean that the drivers of and resistances to the latent and sensible heat exchange are explicitly represented.

The objective of the present paper is to explore whether by using the full energy balance equation as an additional constraint, further insights into the plausibility of closure options can be gained. To this end we make use of the theoretical framework developed by Widmoser (2009, 2010), which makes less assumptions compared to the frequently used Penman–Monteith combination equation (Monteith, 1965) and conveniently allows to separate biologically/physically plausible from implausible solutions. Field data from three different study sites, a temperate mountain grassland, a Mediterranean cork oak plantation and a desert shrub ecosystem are used to test and illustrate our approach.

2. Methods

2.1. Theoretical background

The method used in this paper to separate plausible energy closures from biologically/physically unrealistic ones is based on theoretical developments by Widmoser (2009, 2010), which is briefly summarized in the following.

One way of extending the energy balance, i.e.

$$A = R_N - G = \lambda E + H, \tag{1}$$

where R_N, G, λE and H represent the net radiation, soil heat flux, latent and sensible heat fluxes (all units: J m^{-2} s^{-1}) respectively, is to write:

$$A = [e_s(T_s) - e_a]\frac{c_v}{\gamma(T_s)r_v} + [T_s - T_a]\frac{c_v}{r_H} \tag{2}$$

Here $e_s(T_s)$ and e_a refer to the saturation vapor pressure at the surface temperature and the actual air vapor pressure (Pa), T_s and T_a to the surface and air temperature (°C), c_v to the volumetric heat capacity of moist air at constant pressure (J m^{-3} K^{-1}), $\gamma(T_s)$ to the psychrometric parameter (Pa K^{-1}) as a function of T_s, and r_v and r_H to the surface resistance to water vapor and heat transfer (m s^{-1}).

In Eqs. (1) and (2) the values A, λE, H, T_a, e_a and r_H are assumed to have been directly measured or inferred from measurements through additional models (r_H). Separating the terms with T_s and setting r_H equal to the aerodynamic resistance r_a and r_v equal to the sum of $r_a + r_c$ (r_c = canopy (stomatal) resistance to vapor transport) leads to

$$\frac{e_s(T_s)}{r_1\gamma(T_s)} + T_s = T_a + A\frac{r_a}{c_v} + \frac{e_a}{r_1\gamma(T_a)}, \tag{3}$$

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