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Short communication

On the consequences of the energy imbalance for calculating surface conductance to water vapour

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ABSTRACT

The Penman–Monteith combination equation, which is most frequently used to derive the surface conductance to water vapour (G_s), implicitly assumes the energy balance to be closed. Any energy imbalance (positive or negative) will thus affect the calculated G_s. Using eddy covariance energy flux data from a temperate grassland and a desert shrub ecosystem we explored five possible approaches of closing the energy imbalance and show that calculated G_s may differ considerably between these five approaches depending on the relative magnitudes of sensible and latent heat fluxes, and the magnitude and sign of the energy imbalance. Based on our limited understanding of the nature of the energy imbalance, we tend to favour an approach which preserves the Bowen-ratio and closes the energy balance on a larger time scale.

1. Introduction

Calculating the surface conductance to water vapour (G_s; mol H_2O m^{-2} s^{-1}) from energy balance component measurements is a powerful means for analysing differences in control over water vapour transfer between ecosystems (e.g. Kelliher et al., 1995) and the control exerted by environmental factors (e.g. Vourlitis et al., 2008). Usually G_s is derived by inverting the Penman–Monteith combination equation (e.g. Campbell and Norman, 1998):

$$G_s = \frac{G_a \gamma}{(s(R_n - G) + (Dc_p G_a/P))/\lambda E - s - \gamma} \quad (1)$$

where G_a (mol m^{-2} s^{-1}) is the aerodynamic conductance (assumed to be the same for heat and water vapour transfer), $R_n - G$ refers to the available energy (J m^{-2} s^{-1}), that is the difference between net radiation and soil heat flux (assuming that other energy storage is negligible), λE is the latent heat flux (J m^{-2} s^{-1}), s refers to the slope of the saturation vapour pressure with respect to temperature (K^{-1}), γ is the psychometric 'constant' (K^{-1}), D and P are the vapour pressure deficit and atmospheric pressure (kPa), respectively, and c_p is the specific heat of air (J mol^{-1} K^{-1}). By substituting $(R_n - G)/(1 - \beta)$ for λE, where β is the Bowen-ratio ($H/\lambda E$, where H is the sensible heat flux in J m^{-2} s^{-1}), Eq. (1) may also be written as

$$G_s = \frac{G_a \gamma}{(1+\beta)(s + Dc_p G_a/(P(R_n - G))) - s - \gamma} \quad (2)$$

Eqs. (1) and (2) imply the energy balance to be closed, i.e. the available energy to equal the sum of latent and sensible heat exchange. This assumption is frequently not fulfilled by the eddy covariance (EC) method (Wilson et al., 2002), which is thought to be the most direct micrometeorological technique for measuring surface fluxes (Meyers and Baldocchi, 2005). When using EC data in Eqs. (1) or (2) a decision must be made on how to deal with any energy imbalance either implicitly or explicitly. If Eq. (1) is used with λE as measured, the energy imbalance is attributed to H; if Eq. (2) is used then the energy imbalance is attributed to both λE and H according to the Bowen-ratio. With Eq. (1) the energy imbalance may also be attributed to λE or H, or both, in some other fashion (Twine et al., 2000).

As we will discuss below, the choice of how the energy imbalance is closed may profoundly affect the resulting G_s, a fact which, to our knowledge, has not been widely appreciated up to now, despite a long history of research on the energy imbalance (for a recent review see Foken, 2008). To this end we use one month of data from two contrasting ecosystems—a vigorously transpiring temperate grassland ecosystem in the Austria Alps, and a desert shrub ecosystem in Nevada/USA. To illustrate the nature of the problem and its consequences for estimating G_s, we use five

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different strategies for closing the energy imbalance using bin-averaged diurnal courses of the variables of Eqs. (1) and (2).

2. Materials and methods

The temperate grassland site is situated in the Stubai Valley (Austria) close to the village of Neustift (Hammerle et al., 2008; Wohlfahrt et al., 2008a). The desert flux tower is part of the Mojave Global Change Facility (MGCF) in the Northern Mojave Desert (Nevada/USA; Wohlfahrt et al., 2008b). A closed-path EC system was used at the temperate grassland site, an open-path system at the desert site to determine the fluxes of latent and sensible heat (Aubinet et al., 2000). Other input parameters for Eqs. (1) and (2) have been determined by standard meteorological measurements. Measured soil heat flux was corrected for the energy storage in the soil layer above the heat flux plates based on the calorimetric method (Sauer and Horton, 2005). The grassland data were gathered during May 2006, the desert data in March 2006. The various derived variables in Eqs. (1) and (2), including G_a and its stability correction, were calculated according to Ham (2005).

The five alternative methods of closing the energy imbalance we explored include the following:

(1) the energy balance is closed each half-hourly period by attributing the residual energy to H which is implied if Eq. (1) is used along with measured λE; referred to as G_{s_H};
(2) the energy balance is closed each half-hourly period by attributing the residual energy to λE (Eq. (1)); referred to as $G_{s\_\lambda E}$;
(3) the energy balance is closed each half-hourly period by attributing the residual energy to both H and λE according to the Bowen-ratio, which is implied if Eq. (2) is used; referred to as G_{s_β};
(4) both H and λE are modified each half-hourly period by a factor which closes the energy balance on some longer time interval (monthly in the present case), which implies that during each half-hourly period the energy balance may not necessarily be closed; by using Eq. (1) any residual energy is, as with method (1) above, implicitly assigned to H; referred to as G_{s_EBR};
(5) the energy balance is closed each half-hourly period by setting the available energy ($R_n - G$) equal to ($H + \lambda E$); note that this method implicitly conserves the Bowen-ratio as measured H and λE remain unchanged and therefore both Eqs. (1) and (2) may be used; referred to as $G_{s\_R_n - G}$.

Note that any changes in H (methods 1, 3 and 4) will change calculated G_s also through changes in G_a which depends on H through the corrections for atmospheric stability (Ham, 2005).

3. Results

As anticipated, most of the available energy was attributed to latent instead of sensible heat in the temperate grassland, while the reverse was true for the desert shrub ecosystem (midday Bowen-ratios of 0.6 and 2.0, respectively). On average, latent and sensible heat fluxes fell 18% short of the available energy in the temperate grassland ecosystem ($H + \lambda E = 0.82$ ($R_n - G$); $r^2 = 0.98$), while the energy balance of the desert ecosystem was perfectly closed on average ($H + \lambda E = 1.00$ ($R_n - G$); $r^2 = 0.85$), albeit with larger, both positive and negative, absolute deviations (Fig. 1). After correcting for the average energy imbalance, available energy was underestimated at the

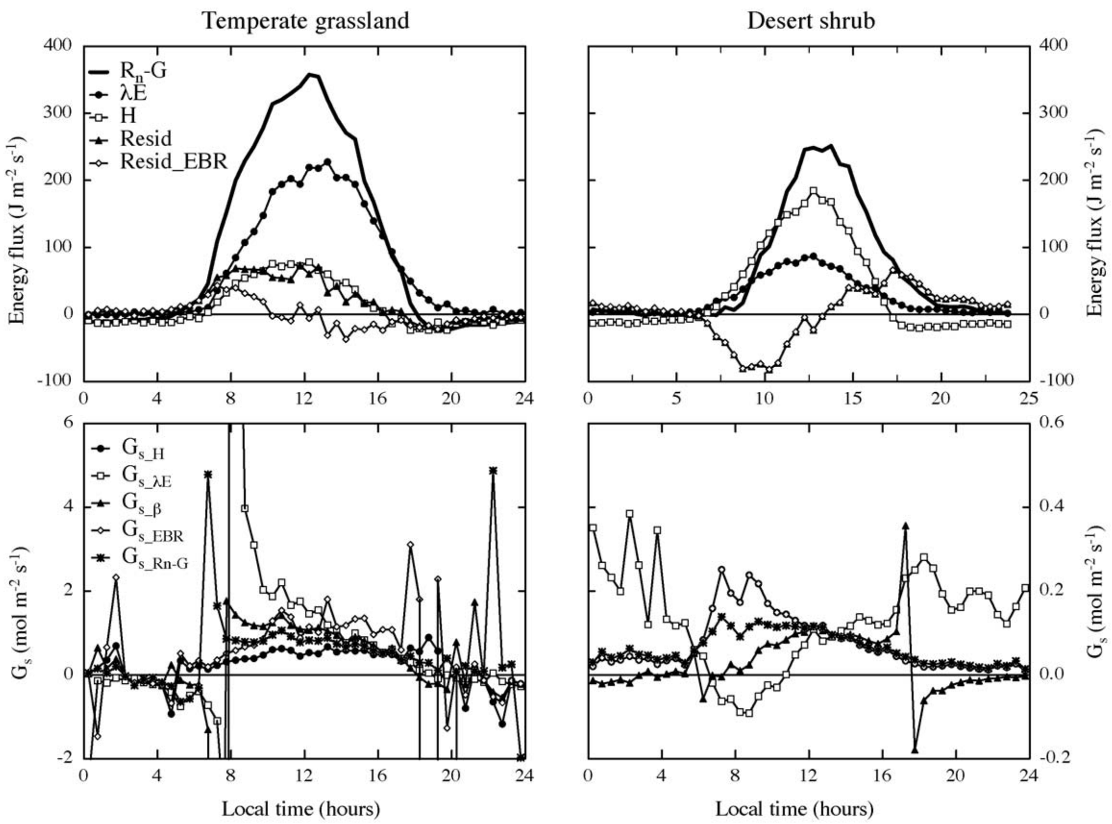

Fig. 1. Energy balance components (upper panels) and surface conductance (G_s) calculated with five different energy imbalance closure approaches (lower panels) for a temperate grassland (left) and a desert shrub ecosystem (right). G_s values exceeding the y-axis scale have been truncated. Note the differences in scale for G_s of the temperate grassland and desert shrub ecosystem. Resid refers to the residual energy as measured, while Resid_EBR to the residual energy after correcting for the long-term energy imbalance (i.e. method 4). Because the long-term energy balance is almost perfectly closed at the desert site, Resid and Resid_EBR and G_{s_H} and G_{s_EBR} lines overlap in the upper and lower panels, respectively, on the right side.

grassland site in the morning and overestimated in the afternoon (Fig. 1).

Because the available energy was generally underestimated during daytime at the temperate grassland site, assigning the residual energy to H (method 1) resulted in the lowest estimates of G_s while assigning the residual energy to λE (method 2) resulted in the highest estimates (Fig. 1). In contrast, because the available energy was overestimated in the morning and underestimated in the afternoon at the desert shrub ecosystem, assigning the residual energy to H yielded very high G_s values in the morning, while assigning the residual energy to λE caused G_s to become negative in the morning (Fig. 1). Attributing the residual energy to λE according to the Bowen-ratio during each half-hourly period (method 3) resulted in an abrupt increase of G_s at the grassland site in the morning followed by steady decline during the rest of the day (Fig. 1). At the desert ecosystem, this closure strategy caused G_s to increase from low morning values to a peak at noon and then to decrease again later in the day, with a step-change towards negative values once the Bowen-ratio became negative (Fig. 1). Closing the energy balance on average (method 4) resulted in G_s being intermediate between G_{s_H} and $G_{s\_\lambda E}$ at the grassland site, except for the later afternoon when overestimation of the available energy (and thus high λE values) yielded the highest G_s values (Fig. 1). Because the energy balance was perfectly closed on average at the desert shrub ecosystem, virtually no change was observed with this closure strategy and the G_s values overlapped with G_{s_H} (Fig. 1). Assigning the energy imbalance to the available energy (method 5) yielded G_s values in between the other methods (Fig. 1).

4. Discussion and conclusion

Because the Penman–Monteith combination equation, which is most frequently used to derive the surface conductance to water vapour (G_s), assumes the energy balance to be closed, any energy imbalance (positive or negative) will affect the calculated G_s. Here we explore five possible approaches of closing the energy imbalance and show that calculated G_s may exhibit contrasting diurnal courses that may differ by a factor of two or more (under daytime conditions) from each other and may even differ in sign under certain conditions (Fig. 1). Depending on the relative magnitudes of H and λE, and the magnitude and sign of the energy imbalance, the various energy balance closure approaches can produce widely varying calculated G_s values indicating that the problem is likely to be site-specific.

Attributing the residual energy to either H, λE or the available energy alone (methods 1, 2 and 5) assumes that some deficiency in the measurement of these terms leads to the energy imbalance. According to Foken (2008), instrument or technical issues cannot or can only partly explain the energy imbalance. On the other hand, several recent publications have reported problems with energy flux measurement instrumentation and data processing (Loescher et al., 2005; Ibrom et al., 2007; Burba et al., 2008; Mauder et al., 2008; Haslwanter et al., 2009) and that careful quantification of the available energy and usually neglected energy balance components (e.g. energy flux to photosynthesis, heat storage in biomass) may in some cases greatly improve energy balance closure (Meyers and Hollinger, 2004; Jacobs et al., 2008). In fact, the opposing sign of the energy imbalance at the desert site may be indicative of a shortcoming of the calorimetric method (Sauer and Horton, 2005) to account for heat storage above the soil heat flux plates (Heusinkveld et al., 2004). Foken (2008) concludes that the energy imbalance is mainly caused by larger eddies, created by heterogeneities at the landscape-scale that are not adequately sampled by EC flux towers (see also Mauder et al., 2007). Provided that these large-scale eddies (or low-frequency energy flux contributions) are characterised by similar Bowen-ratios as measured by the EC flux tower, closing the energy imbalance by conserving the Bowen-ratio may represent a preliminary, engineering-type approach for solving the energy imbalance (Twine et al., 2000; Foken, 2008). However, doing so may lead to spurious G_s values when the closure operation changes H and λE by large amounts. This occurs frequently with method (3), which forces closure according to the Bowen-ratio during each averaging period. Longer than the typical 30 min averaging periods may be needed to reduce this problem, as Finnigan et al. (2003) and Mauder and Foken (2006) have shown the energy imbalance to improve as the averaging time is increased. Method (4), which adjusts λE according to the long-term (1 month in the present case) energy imbalance, may be superior in this regard. However any residual energy on a half-hourly basis after closure has to be attributed to λE, H or $(R_n - G)$ also in this case, i.e. by using the other methods (1–3, 5).

In conclusion, our analysis shows that the method by which the energy imbalance is accounted for when using the inverted Penman–Monteith combination equation to calculate G_s may fundamentally affect the value of G_s that is calculated. This is an implicit property of the Penman–Monteith equation which assumes the energy balance to be closed. Therefore, when calculating G_s it is advised to carefully consider how the energy balance will be closed—either implicitly by choosing an equation which is formulated in terms of λE (Eq. (1)) or β (Eq. (2)) or explicitly by choosing some other form of closure. In any case, the equations used to calculate G_s and the energy balance closure need to be articulated. In order to quantify the uncertainty associated with G_s it may be a useful exercise to calculate G_s for the two extreme scenarios which attribute the energy imbalance to either only H (method 1) or λE (method 2).

Given our current (limited) understanding of the nature of the energy imbalance (Foken, 2008), we tend to favour our method (4) because it preserves the Bowen-ratio and closes the energy balance on a larger time scale. But clearly there is a need for further research on the causes of and practical approaches for correcting the energy imbalance. Independent methods of estimating λE (e.g. sap flow, lysimeters, chambers, water balance studies) may help to constrain the uncertainty associated with G_s.

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