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# Energy balance closure at a variety of ecosystems in Central Europe with contrasting topographies

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## ABSTRACT

A long-standing problem in micrometeorology is that at most eddy covariance sites around the world, the sum of the sensible and latent heat flux measurements is less than the available energy, resulting in the so-called energy balance closure problem. This study utilised the national network of eddy covariance towers in the Czech Republic to examine the degree of energy balance closure at sites covering a wide variety of vegetation types and terrain complexities. The degree of energy balance closure at each site varied depending on the method used to calculate the closure fraction. When the closure was computed using linear regressions of half-hourly sums of turbulent heat fluxes against half-hourly available energy values, closure ranged from 0.68 (beech forest) to 0.81 (spruce forest). However, when closure was computed using the bulk energy balance ratio method, values ranged from 0.61 to 0.73. Highest closure occurred in moderately unstable atmospheric conditions, while closure also increased with increases in the correlation coefficients for vertical wind velocity and water vapour, and vertical wind velocity and sonic temperature. Lowest closure was found at a beech forest in the Carpathian Mountains, where evidence suggested that the complex topography to the south of the eddy covariance tower was influencing the airflow and resulting in poor energy balance closure results. Energy balance closure was also particularly low at a rapeseed cropland, and this was attributed to the low frequency of moderately unstable to strongly unstable conditions at the site.

## 1. Introduction

Exchanges of carbon, water, and energy between the Earth's surface and the atmosphere are extremely important in hydrological, climatological and biological processes. Our understanding of these processes largely relies on observations from eddy covariance (EC) flux measurement towers (Stoy et al., 2013). The EC method involves determination of surface fluxes using high frequency measurements of vertical wind velocity, sonic temperature and the density of gases, such as water vapour and carbon dioxide ($CO_2$). However, a long-standing problem in micrometeorology is that at most EC sites around the world, the sum of the sensible and latent heat flux measurements ($H + LE$) is less than the available energy (Aubinet et al., 2000; Wilson et al., 2002a; Foken, 2008; Foken et al., 2011; Leuning et al., 2012). This results in a violation of the law of conservation of energy, and the so-called energy balance closure (EBC) problem.

The energy balance equation can be written as follows (all units are in W $m^{-2}$):

$$R_n - G - J = H + \mathrm{LE} \quad (1)$$

where $H$ is the energy transferred between the surface and the atmosphere as sensible heat, LE is the energy flux associated with the evapotranspiration of water vapour, $J$ is the energy stored within the canopy air and biomass and the energy absorbed during the process of photosynthesis, $G$ is the soil heat flux and $R_n$ is the net radiation. The left hand side of Eq. (1) represents the available energy (AE), which should be balanced by an equivalent transfer of heat to or from the atmosphere through the sum of the turbulent heat fluxes, LE and $H$. Wilson et al. (2002a) found that on average the sum of the turbulent fluxes was approximately 20% less than the available energy across 22 FLUXNET sites with contrasting ecosystems and climates, while more recent multi-site studies by Franssen et al. (2010) and Stoy et al. (2013) found similar results. Energy balance closure is directly relevant to the evaluation of LE and $H$. In addition, because there is similarity in the atmospheric transport mechanisms for the different scalars measured by EC, the EBC problem is also potentially relevant in the interpretation of other fluxes, such as $CO_2$ (Wilson et al., 2002a; Barr et al., 2006).

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Therefore, lack of EBC has important implications when trying to estimate terrestrial energy, water and carbon budgets using EC flux measurements.

Many causes of the lack of EBC have been proposed in previous studies. These causes can be split into errors that result in an overestimation of AE or errors that result in an underestimation of the turbulent fluxes. Possible causes of an overestimation in AE include: overestimation of $R_n$ measurements and the incorrect quantification of soil, air column and vegetation energy storage terms (Foken, 2008). While potential reasons for the underestimation of LE and/or $H$ include: neglecting horizontal and/or vertical advection fluxes associated with complex terrain or heterogeneities in surface cover (Oncley et al., 2007); loss of high frequency covariance due to improper instrumental set-up, inadequate sampling frequency and/or attenuation of the high frequency fluctuations of water vapour in closed-path EC systems (Leuning et al., 2012); and loss of low frequency covariance due to EC averaging periods being insufficient to capture large-scale turbulent structures (Foken, 2008).

Improvements in the precision of net radiometers make it unlikely that errors in $R_n$ measurements are the main cause of the EBC problem (Foken, 2008). In addition, improvements in EC sensors, correction methods and data quality checking procedures have improved the reliability of the EC method and its ability to accurately measure the high frequency range of the turbulent spectra (Foken et al., 2006). A possible explanation for the lack of EBC, that has received a lot of attention in recent years, is the problem of low frequency turbulence that is not captured by the EC instrumentation because the averaging periods (typically 30-min) are inadequate (Mauder et al., 2010; Stoy et al., 2013; Charuchittipan et al., 2014; Eder et al., 2014; Gao et al., 2017). This hypothesis suggests that a single EC tower, averaging over 30 min, may be unable to detect large, slow-moving turbulent circulations that result from landscape heterogeneity (Foken et al., 2011; Charuchittipan et al., 2014). Other authors, such Leuning et al. (2012), argue that unmeasured or inadequately measured energy storage terms are probably the dominant contributor to the lack of EBC at a lot of sites.

Panin and Tetzlaff (1999) observed a link between surface heterogeneity and lack of EBC, while Stoy et al. (2013) used an extensive dataset, involving 173 ecosystems, from the FLUXNET database to analyse the relationship between EBC and landscape heterogeneity and surface type. It was found that EBC was generally higher at sites with homogenous vegetation cover, with highest closure in evergreen broadleaf forests and savannahs and lowest in crops, deciduous broadleaf forests, mixed forests and wetlands. Other studies have explored how EBC is influenced by variation in meteorological variables such as friction velocity, $u_*$, and atmospheric stability (Barr et al., 2006; Franssen et al., 2010). These studies found that EBC generally improves with increasing $u_*$ and instability, because the conditions of Taylor's hypothesis are better fulfilled in conditions with high $u_*$ and convection is not suppressed in unstable conditions. Further studies of this kind, at sites covering a wide variety of vegetation types and terrain complexities, will help to provide a better understanding about the relationship between EBC and variation in meteorological variables.

In Gao et al. (2017) large phase differences in the signals of vertical wind velocity and water vapour were associated with large eddies (linked to entrainment and advection) and resulted in increased residuals in the energy balance at a cotton field in California. We hypothesise that when the covariance of the turbulent quantities is small but the product of the standard deviations is large (i.e. low correlation coefficient), then this is an indication that the two quantities are out of phase. The relationships between the degree of EBC and the correlation coefficients for vertical wind velocity and water vapour ($R_{wq}$) and vertical wind velocity and sonic temperature ($R_{wT}$), were analysed at several sites in this study.

Ideal EC sites have an extended flat and homogenous surface in the upwind direction. However, further knowledge about the quality of EC measurements in complex, non-ideal sites is crucial, especially considering the high proportion of the world's ecosystems in mountainous terrain. Mountains cover 25% of the Earth's total land surface area (Stiperski and Rotach, 2016), while approximately 30% of the world's forests are in mountainous terrain (Kapos et al., 2000). Some studies have analysed aspects of EBC in mountainous environments (Turnipseed et al., 2002; Hiller et al., 2008). These aspects include: the importance of correcting the incoming short-wave radiation for the angle between the inclined surface and the radiation sensor and differences in EBC during upslope and downslope winds. However, overall there have been a lack of studies that have analysed EBC at different ecosystems in sloping and/or complex terrain, despite the importance of measurements in such locations.

This study utilises the national network of EC towers in the Czech Republic, which are part of the Czech Carbon Observing System (CzeCOS), to analyse EBC at sites covering a wide variety of vegetation types and terrain complexities. This network includes mountain and highland spruce forests, a mountain beech forest, a highland cropland and a wetland. The aims of this study are to analyse the influence of vegetation type and terrain complexity on EBC, to examine the relationship between EBC and meteorological variables, to explore how post processing procedures influence EBC and to establish whether the causes of lack of EBC are related to improperly measured storage terms or the inability of the EC system to accurately measure turbulent fluxes.

## 2. Sites and instrumentation

### 2.1. Site descriptions

This study uses measurements made by the CzeCOS (http://www.czecos.cz/) network of EC towers. Some of the sites are also part of international EC observation networks. Bílý Kříž (BK) and Třeboň (TR) are both part of FLUXNET, while BK is also part of ICOS (Integrated Carbon Observation System). The main characteristics of the sites covered by the CzeCOS network are presented in Table 1 and references with more detailed descriptions of some of the sites are also given. This study focuses on 3 years of measurements made between 2012 and 2014 (with the exception of Křešín (KR) and TR, where data was only available for 2014 and 2012–2013, respectively). The water table at TR (a sedge-grass marsh) during the study period was above the soil surface 39% of the time, with a maximum level of +1.78 m (relative to the soil surface) in June 2013 and a minimum level of −0.45 m in August 2013. Generally (90% of the time), the water table was between −0.35 m and 0.20 m. From the beginning of 2014 to the end of July, measurements at KR took place above a rapeseed crop that was not irrigated. This crop was harvested between 26 and 27 of July.

The TR site is flat, while Rájec (RA) and KR are situated on gentle slopes. However, both BK and Štítná (ST) feature more complex terrain (Fig. 1). The BK site is situated on a SSW-oriented planar slope that is approximately 100 m downslope of a W–E oriented mountain crest (Sedlak et al., 2010). Upslope/downslope and cross-slope directions are quite well defined at the site. The airflow at the site is strongly modified by the terrain so that upslope (southerly) and downslope (northerly) winds dominate (Sedlak et al., 2010). The ST site is situated on a WSW-orientated slope, with upslope winds from the west and downslope winds from the east. However, the terrain is quite complex, involving more than one planar slope. Immediately to the south of the mast is a gentle SW-orientated slope. This slope continues for 150 m until it reaches a small creek. On the southern side of this creek the slope changes to a N-orientated slope and this continues for several hundred meters south of the mast. To the north of the mast, a gentle N-orientated slope is present between the mast and some farmland.

### 2.2. Instrumentation

An overview of the most relevant instrumentation at each site is given in Table 2. For effective comparison of measurements, the