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Impacts of soil heat flux calculation methods on the surface energy balance closure

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ABSTRACT

Quantifying uncertainty in determining the surface soil heat fluxes (G_0) to close the surface energy balance in micrometeorological studies remains an open question. While numerous methods have been proposed to determine G_0 and have been validated individually, few studies have cross-evaluated these methods to examine how the derived G_0 from different methods affects the closure of the surface energy balance. Using data measured at an arid shrub-land site during summertime, nine different methods were evaluated ranging from conventional heat-storage calorimetry to methods derived directly from the heat transfer equation. Apart from the entire dataset, two subsets were used; one with minimal variation from idealized diurnal radiation cycles and the other with highly variable radiation conditions. Under the entire dataset, the performance of the methods varied while there was a distinct drop-off in the level of closure under the variable radiation conditions. The methods that allowed for the most variation in inputs between time steps performed better than those that used diurnal or constant input values. Because of this, a calorimetry method and Green's function-based method are more highly recommended than other methods.

1. Introduction

The surface energy imbalance in micrometeorological studies remains an unsolved problem (Foken et al., 2011). At most flux sites, the sum of the sensible heat (H) and latent heat (LE) fluxes is on average 10–30% less than the available energy ($A = R_n - G_0 - S$ where R_n is the surface net radiation, G_0 is the soil heat flux at the surface, and S is changes in heat storage in the air and vegetation below the flux measurement height) (Wilson et al., 2002; Liebethal et al., 2005; Foken, 2008; Cava et al., 2008; Jacobs et al., 2008; Gentine et al., 2012; Stoy et al., 2013). Theoretical, instrumental, and methodological reasons have been proposed to explain the reasoning for the observed energy imbalance problem in the surface energy budget. This includes instrument footprint-scale mismatch, advective flux divergence, low frequency and large scale turbulent motions, and measurement and calculation errors in all components of the surface energy balance (e.g., Wilson et al., 2002; Mauder et al., 2007; Oncley et al., 2007; Foken, 2008; Foken et al., 2011; Leuning et al., 2012; Wohlfahrt and Widmoser, 2013).

Efforts have been made to examine the influence of the potential error sources on the lack of energy closure. Even with careful consideration and investigation of experimental design, post-field data processing and instrumentation, lack of energy closure is still reported (Mauder and Foken, 2006; Kohsiek et al., 2007; Mauder et al., 2007; Oncley et al., 2007; Cava et al., 2008; Foken, 2008; Leuning et al., 2012; Wohlfahrt and Widmoser, 2013) even though measurements, flux corrections and, data processing have been studied extensively (Mauder and Foken, 2006; Oncley et al., 2007; Kohsiek et al., 2007; Mauder et al., 2007). Of the terms in the energy balance, R_n is a relatively accurate term with at most a 5% error (Kohsiek et al., 2007). Mauder and Foken (2006) found that rigorous post-field data processing and flux calculation can reduce the energy balance residuals up to 17%. If appropriate corrections are used, then the errors within the sensible and latent flux calculations can be minimized so their impact upon the overall energy balance imbalance is reduced leaving G_0 as a potential source of systematic error.

Soil heat flux is commonly measured by soil heat flux plates at some depth (Z_m) below the surface (G_{zm}). Because of this, changes in the heat storage in the soil layer above the heat flux plates (S_G) needs to be determined G_0 ($G_0 = G_{zm} + S_G$). Some methods of calculating G_0 do not require an S_G term because they calculate G_0 directly at the surface using the thermal properties of the soil

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seeded by direct measurements. G_{zm} has to be measured deep enough in the soil so the flux plate and other instruments are not affected (Mayocchi and Bristow, 1995; Wang and Bras, 1999; Kustas et al., 2000; Ochsner et al., 2007; Gentine et al., 2012; Sun et al., 2013). However, G_{zm} becomes damped and lagged by the soil layer between Z_m and the surface (Z_o) compared to G_0 (Oncley et al., 2007; Foken, 2008; Gao et al., 2010; Sun et al., 2013; Li et al., 2014). Placing heat flux plates very near the surface (within a few millimeters of the surface) is not advisable as the overlying soil can lose contact with the rest of the near-surface soil matrix adversely affecting water and heat flow (Mayocchi and Bristow, 1995; Wang and Bras, 1999; Ochsner et al., 2007; Núnez et al., 2010; Leuning et al., 2012). Burying the soil heat flux plate forces an accounting for S_G since it can be as large as the measured in-soil heat flux (Mayocchi and Bristow, 1995; Kustas et al., 2000; Heuskinveld et al., 2004; Yang and Wang, 2008; Foken, 2008; Hsieh et al., 2009; Higgins, 2012) but quantifying S_G is site specific due to differences in vegetation, soil, and topography across different landscape (Cava et al., 2008).

Multiple methods exist to calculate G_0 from G_{zm} to soil and surface temperatures. Calorimetry is the typical field-based method but it requires significant knowledge about the site's soil characteristics and multiple in-soil measurements. Other methods require only one measurement (surface temperature or G_{zm}) and minimal knowledge of soil properties. The use of the best methods to calculate G_0 can reduce uncertainty in the overall energy balance and identify the causes for the lack of closure at micrometeorological flux sites. Previous studies have examined individual aspects of how different calculation methods affect the soil heat flux estimates such as phase lag (Gao et al., 2010; Sun et al., 2013), missing energy pathways (Higgins, 2012), and variation in the incoming radiation (Gentine et al., 2012). Similar analyses have also been done as parts of large field campaigns (e.g. EBEX) (Oncley et al., 2007) and general reviews regarding the energy budget closure problem (e.g., Foken, 2008; Leuning et al., 2012).

As newer methods to calculate G_0 are derived and proposed, they are compared to calorimetry as validation then used in energy balance calculations to test their efficacy. However, few studies have compared multiple methods and the ones used in these studies have minimal overlap (e.g., Liebethal and Foken, 2007; Venegas et al., 2013; Li et al., 2014). Nine different methods to calculate the soil surface heat flux are presented and compared; each requiring different input soil parameters and measurements. There are similarities between some of the methods but all are treated independently. The objective is to compare the practical applications of each method and their ability to close the energy balance for a typical experimental set-up and flux calculations. The focus of this study is not on identifying and reducing possible error sources from other components of the surface energy balance equation (i.e., H, LE, and R_n) or on deriving and improving the methods presented. Therefore, discussion of the turbulence or stability conditions or of measurement and flux correction errors is beyond the scope of this study. Section 2 describes the data and site used, Section 3 gives an overview of the methods and analysis used, Section 4 presents the results, Section 5 discusses the issues that affected the closure rates and G_0 calculations and recommends the best methods, and conclusions are in Section 6.

2. Data

2.1. Experiment site

Data were collected from an eddy-covariance tower located in the Birch Creek Valley in southeast Idaho (44°08’48”N, 112°57’10”W) from June 25, 2013 until September 15, 2013. The site had short, intermittent vegetation cover comprised mainly of sagebrush no taller than 0.75 m with scattered short grasses between and around the brush. Fig. 1 is an image of the valley and a picture of the tower at the site. The terrain overall sloped approximately 5% from the north to the south with mountains located to the west (4.5 km to peaks) and east (5.5 km to peaks) of the tower. The terrain locally sloped downward to the east toward the center axis of the valley. The soil around the tower site was a sandy-loam with a population of stones and gravel within the matrix. The eddy covariance systems on the tower consisted of a sonic anemometer (model CSAT3, Campbell Scientific Inc.) and open-path infrared gas analyzer (model LI7500A, LiCor Inc.) at 3 m, with a co-located temperature/relative humidity sensor (HMP45C, Campbell Scientific, Inc.). Also used were a net radiometer (7.5 m, CNR2, Kipp & Zonen) and downward looking infrared thermometer (3.5 m, SI-111 Apogee Instruments Inc.). Buried near the tower was an array of soil sensors including seven soil temperature sensors (0.025, 0.05, 0.075, 0.10, 0.15, 0.20, and 0.25 m, 109SS, Campbell Scientific Inc.), five volumetric water content reflectometers (0.025, 0.05, 0.10, 0.15, and 0.20 m, CS616, Campbell Scientific Inc.), and two self-calibrating soil heat flux plates at 0.06 m (HFPSC-01, HuskeFlux Thermal Sensors).

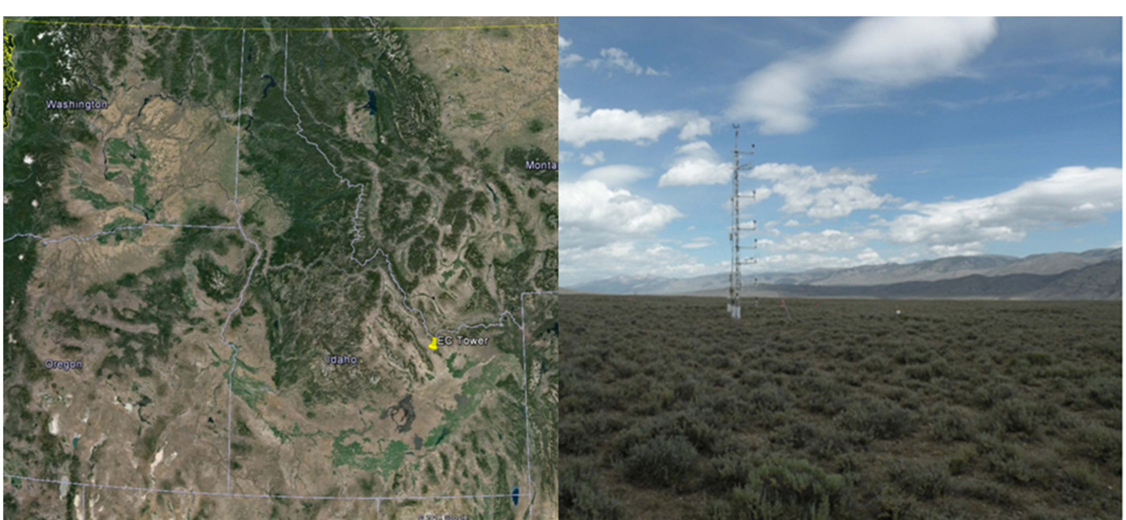

Fig. 1. Google Earth image of the overall valley with the site denoted by the pin (left) and picture of the measurement site looking to the north (right).