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Determination of soil ground heat flux through heat pulse and plate methods: Effects of subsurface latent heat on surface energy balance closure

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ABSTRACT

The soil heat flux plate method is popularly applied in surface energy balance studies. Previous studies have shown that impervious plate blocks the flow of water and vapor within soil. Soil heat flux is generally commonly measured below surface, and its exact constitution is required in calculating surface energy balance. When subsurface evaporation occurs, subsurface latent heat sink constitutes an important proportion of the apparent ground heat flux. However, the plate method fails to detect such occurrence. In aboveground meteorological measurement, evaporated vapor moving out of soil profile is also being detected and the subsurface latent heat sink is recognized as part of turbulent latent heat flux. Thus, caution should be exercised when excluding the potential error from double counting of subsurface latent heat sink in surface energy balance evaluation. In this study, two common combination methods were used to determine the ground heat flux without latent heat sink (G_0). One method is a combination of gradient-based heat pulse measurements and calorimetric method (GradC), and the other method is a combination of plate measurements at shallow depths and calorimetric method (PlateC). Results demonstrated that, in contrast to the PlateC method, the GradC method minimized the disturbance in soil structure and reduced the disruption in heat and water flow. Furthermore, the estimated G_0 from the PlateC method was only 49.2% of that of the GradC method during daytime. Moreover, surface energy balance closure (EBC) was evaluated using the estimated G_0 and aboveground turbulent energy flux data. In comparison with the PlateC method, the GradC method improved the surface EBC from 79.3% to 87.7% during daytime. In summary, accurate knowledge on the composition of ground heat flux and the location of water evaporation is necessary to calculate surface energy balance during micro-meteorology measurements.

1. Introduction

Understanding the energy exchange between land surface and atmosphere is important in simulating hydrological, atmospheric, and ecological processes (Baldocchi et al., 2001; Stoy et al., 2009). However, the surface energy imbalance in micrometeorological studies remains unsolved (Wilson et al., 2002; Foken, 2008; Foken et al., 2011; Stoy et al., 2013; Russell et al., 2015). In the past decades, imbalance in energy budget has been widely studied, and the average energy balance closure (EBC) from the eddy covariance (EC) measurement ranges between 0.75 and 0.87 at most flux sites (Stoy et al., 2013).

The energy balance equation is generally expressed as

$$R_n - G_0 = H + LET \tag{1}$$

where R_n is the net radiation (W m^{-2}); H and LET are the surface–atmosphere turbulent fluxes of sensible heat and latent heat (W m^{-2}), respectively; G_0 is the ground heat flux at soil surface without latent heat sink (W m^{-2}).

The left side of $R_n - G_0$ is often termed as the available energy, and EBC is denoted as the ratio of turbulent fluxes ($H + LET$) to available energy. Notably, Eq. (1) assumes that evaporation occurs at the soil surface (Wang and Bou-Zeid, 2012). This condition only occurs on soils with large water content and that immediately following rainfall (Heitman et al., 2008a). If the evaporation front migrates downward into the subsurface, then the evaporation actually occurs at a certain depth below the surface (Mayocchi and Bristow, 1995; Heitman et al., 2010). Thus, accurate knowledge on the composition of soil ground heat flux is necessary because a large proportion of apparent ground heat flux is contributed by subsurface latent heat sink. Meanwhile, in aboveground EC measurement, soil water evaporated vapor combines

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Nomenclature

d	Diameter of heat flux plate
E	Soil evaporation rate
EBC	Energy balance closure
EC	Eddy covariance
ET	Evapotranspiration rate
f	Geometrical factor associated with the dimensions of heat flux plate
G_0	Ground heat flux without latent heat sink
G_a	Apparent soil heat flux
G_p	Corrected apparent soil heat flux determined with the plate method
G_{pu}	Uncorrected apparent soil heat flux measurement obtained using the plate method
G_r	Apparent soil heat flux at a reference depth
GradC	Combination of gradient-based heat pulse measurements and calorimetric method
H	Surface–atmosphere turbulent flux of sensible heat
L	Volumetric latent heat of vaporization
LET	Surface–atmosphere turbulent flux of latent heat
PlateC	Combination of heat flux plate measurements and calorimetric method
P_t	Thickness of heat flux plate
R_n	Net radiation
T	Soil temperature
t	time
z	Soil depth

Greek symbols

λ_p	Plate thermal conductivity
λ_s	Soil thermal conductivity
ΔS	Change in soil heat storage
$\Delta T/\Delta z$	Soil temperature gradient

Subscripts

i	Index variables for soil depth layers
j	Index variables for time steps

with transpiration vapor and is detected and counted as part of turbulent latent heat flux. Thus, G_0 in Eq. (1) should exclude the proportion of subsurface latent heat sink. An accurate understanding of the subsurface latent heat sink dynamics is required to avoid double counting error in EBC calculation.

The heat flux plate method is commonly used for apparent soil heat flux measurement at present (Sauer et al., 2003; Heusinkveld et al., 2004; Sauer et al., 2007). The plate embeds a thermopile in a thin disk with a fixed thermal conductivity, and the measured thermopile voltage output is converted into heat flux. Heat flow divergence or convergence may be induced in plate measurements because of differences between plate and variable soil thermal conductivities (Philip, 1961; Sauer et al., 2003; Liebethal and Foken, 2006). This error can be corrected if soil thermal conductivity (λ_s), plate thermal conductivity (λ_p), and plate dimensions are known (Philip, 1961). However, the continuous λ_s information in many applications is not commonly available under field conditions (Ochsner et al., 2006). Heat flux plates are generally placed horizontally at depths between 2.5 and 10 cm (Sauer, 2002) but are mostly positioned at depths between 5 and 10 cm (Liebethal et al., 2005; Lindroth et al., 2010; Evett et al., 2012). In some cases, plates are situated at shallow depths (e.g., $\leq$ 2 cm) to reduce the magnitude of heat storage correction in the layer above the plates (e.g., Heusinkveld et al., 2004; Amiro, 2009; Evans et al., 2012; Higgins et al., 2013; Ma et al., 2014; Chow et al., 2014). Owing to the impervious plate design, the plate method exerts a large disturbance on soil structure and blocks heat and fluid flow (Ochsner et al., 2006). The latent heat sink occurring within soil cannot be measured properly. Moreover, divergence of heat flow may be caused by thermal contact resistance at the plate–soil interface in plate measurements (Sauer et al., 2003; Ochsner et al., 2006).

Unlike the plate method, the gradient method based on the heat pulse technique usually possesses a small needle diameter and presents advantages of minimized soil disturbance. Cobos and Baker (2003) and Ochsner et al. (2006) reported the good performance of the heat pulse method on soil heat flux measurement both in the laboratory and field. Moreover, the heat pulse method provides a dynamic determination of soil temperature and thermal properties (e.g., soil thermal conductivity and soil volumetric heat capacity) at various depths and allows calculation of subsurface soil evaporation at fine-scale depth increments (Heitman et al., 2008a,b; Deol et al., 2012).

G_0 can be calculated by a typical combination method by combining the apparent soil heat flux measurement at a reference depth (G_r, W m^{-2}) obtained using the heat pulse or plate method and the change in heat storage (ΔS, W m^{-2}) between the reference depth and the soil surface as follows:

$$G_0 = G_r + \Delta S \tag{2}$$

This research aims to determine the location and magnitude of subsurface evaporation by using the heat pulse technique and obtain the ground heat flux without latent heat sink by using the combination method. The contribution of subsurface latent heat sink on the apparent heat flux at soil surface is illustrated and distinguished. We also use the G_0 of this study and aboveground turbulent energy data to improve the surface EBC. The effect of vapor flow blockage of the plate method on surface energy balance is also demonstrated.

2. Materials and methods

2.1. Experimental setup

Measurements were conducted on a semi-arid grassland of Tongyu Country, Jilin Province, northeastern China (44°59′ N, 122°52′ W) in July 2015 (DOY 187–199). The annual mean air temperature of the study site is 6.3 °C, with a range from −33.7 °C to 38.9 °C. The mean annual precipitation is 320 mm, and approximately 80% of rainfall occurs during summer. The soil at the site is chernozem and possesses a sandy loam texture. The grassland is covered largely by *Chloris virgate* community and annual weed community with a spatially random distribution. *Leymus chinensis* plants are visible on occasion. In the past decade, drought has exacerbated in the study region. Few bare patches are visible occasionally because of drought. During our measurement period, grass was sparse and vegetation height was approximately 3–9 cm.

Turbulent heat flux was measured from the EC system in the site. The EC systems consisted of an ultrasonic anemometer (Model CSAT3, Campbell Scientific Ltd.) and a Li-7500 open path CO_2/H_2O analyzer to continuously measure CO_2, H_2O, and energy fluxes half-hourly. The meteorological instruments on the tower included temperature and humidity measurements (HMP 45CL, Vaisala Inc.), wind speed and direction (034AL and 014AL, Met One Inc.), and radiation measurement (CM21 and CG4, Kipp and Zonen Inc.). The measurement height of the radiation and EC system on grassland was 2 m. The soil heat flux measurements in the current study included four heat flux plate plots and two heat pulse sensor plots. During the measurement period, the underlying surface was flat and all of the sensors were installed on bare soils between grass stems. Pre-experiment showed that the calculated