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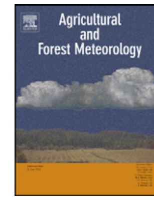

Latent heat in soil heat flux measurements

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ABSTRACT

The surface energy balance includes a term for soil heat flux. Soil heat flux is difficult to measure because it includes conduction and convection heat transfer processes. Accurate representation of soil heat flux is an important consideration in many modeling and measurement applications. Yet, there remains uncertainty about what comprises soil heat flux and how surface and subsurface heat fluxes are linked in energy balance closure. The objective of this study is to demonstrate the presence of a subsurface latent heat sink, which must be considered in order to accurately link subsurface heat fluxes between depths near and at the soil surface. Measurements were performed under effectively bare surface conditions in a silty clay loam soil near Ames, IA. Soil heat flux was measured with heat-pulse sensors using the gradient heat flux approach at 1-, 3-, and 6-cm soil depths. Independent estimates of the daily latent heat sink were obtained by measuring the change of mass of microlysimeters. Heat flux measurements at the 1-cm depth deviated from heat flux measurements at other depths, even after calorimetric adjustment was made. This deviation was most pronounced shortly after rainfall, where the 1-cm soil heat flux measurement exceeded 400 W m^{-2}. Cumulative soil heat flux measurements at the 1-cm depth exceeded measurements at the 3-cm depth by >75% over a 7-day rain-free period, whereas calorimetric adjustment allowed 3- and 6-cm depth measurements to converge. Latent heat sink estimates from the microlysimeters accounted for nearly all of the differences between the 1- and 3-cm depth heat flux measurements, indicating that the latent heat sink was distributed between the 1- and 3-cm depths shortly after the rainfall event. Results demonstrate the importance of including latent heat when attempts are made to link or extrapolate subsurface soil heat flux measurements to the surface soil heat flux.

1. Introduction

Accurate determination of surface soil heat flux is an important consideration in applications ranging from mesoscale land surface modeling (McCumber and Pielke, 1981), to field-scale energy balance in Bowen ratio (Passerat de Silans et al., 1997) and eddy covariance techniques (Shao et al., 2008), to characterizing local temperature variations within managed and natural systems (e.g., Kustas et al., 2000; Kluitenberg and Horton, 1990). Techniques for determining soil heat flux also vary, including both direct measurement (e.g., Ochsner et al., 2006) and estimation based on soil profile temperature distributions (e.g., Horton and Wierenga, 1983) or other measured parameters (e.g., Daughtry et al., 1990). Sauer and Horton (2005) reviewed a variety of techniques that have come to be considered de facto standards for determining soil heat flux, including heat flux plates and the combination method. Yet, there remains uncertainty about what comprises soil heat flux and how surface and subsurface heat flux are linked in energy balance closure (Passerat de Silans et al., 1997; Heusinkveld et al., 2004; Holmes et al., 2008; Wang and Bras, 2009; Holmes et al., 2009).

Some confusion about soil heat flux likely arises from the coupling of water and energy transfer in near surface soil. In describing fully coupled soil heat and water transfer theory, Milly (1982) and Passerat de Silans et al. (1989) used apparent thermal conductivity as a combined term linking simple conduction with latent heat transport by vapor diffusion (i.e., latent heat flux) to describe soil heat flux. However, this fully coupled approach is often absent from implementation and interpretation for pragmatic field measurement campaigns aimed at describing surface energy balance, i.e., soil heat flux is often treated as simple conduction.

When soil heat flux is measured at a subsurface depth, correction for heat terms between the surface and the measurement depth is necessitated, i.e., the commonly used combination method (Fuchs and Tanner, 1968) includes correction for sensible heat storage in the soil layer between the measurement depth and the soil surface, based on temperature change with time and soil heat

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capacity. Massman (1993) indicated that heat flux estimates could include errors up to 10% of the total heat flux when inaccurate estimates of the soil condition are used to determine this heat storage term. Ochsner et al. (2007) suggested that, when neglecting the heat storage term, soil heat flux measured at the 6-cm soil depth might underestimate surface heat flux by more than 50%. Owing to concerns with the link between surface and subsurface heat flux, Heusinkveld et al. (2004) suggested "burying the sensor as close to the surface as possible" in dry, bare soil with a very high surface heat flux. However, the presence of a drying front may limit such an installation approach in conditions where subsurface soil moisture, and hence latent heat of vaporization of soil water, is important (Sauer and Horton, 2005). Improved measurements of soil temperature and soil heat capacity can account directly for sensible heat storage, but not directly for latent heat.

de Vries and Philip (1986) discussed considerations for determining soil heat flux at multiple depths in the null-alignment method. They acknowledged the possibility of a subsurface latent heat sink and argued for its important impact on accurately calculating soil heat flux with depth. Their argument was based on local average soil water evaporation rates and divergence in the subsurface temperature gradient. Mayocchi and Bristow (1995) reiterated this argument, and using an estimated strength of the latent heat flux term from de Vries and Philip (1986), demonstrated subsurface energy balance closure. Though these arguments may indeed be valid, they are based primarily on approximation of unmeasured subsurface terms (i.e., latent heat and soil heat flux).

Debate about the presence of subsurface heat sink terms remains active as estimates of soil heat flux are required in new applications such as remote sensing. Holmes et al. (2008) use an approximated subsurface heat sink term, which they attribute to both sensible and latent heat components of the surface energy balance, to link surface temperatures to subsurface temperature distributions. Using a fitting approach, they concluded that these subsurface terms must be included to describe how the surface heat flux propagates through the profile. Their approach was questioned by Wang and Bras (2009), who argued that this description of the soil heat flux was invalid, particularly the use of a subsurface sensible heat flux that coincided with a surface sensible heat flux term. Further explanation of terms was provided in Holmes et al. (2009).

Overall, the understanding of how subsurface soil heat fluxes are linked to the soil surface would be improved by some clear, measurements and analysis indicating the presence of a subsurface heat sink. The objective of this report is to illustrate the presence of a subsurface latent heat sink, which must be considered in order to accurately link subsurface heat fluxes between depths near the soil surface. Measurements of subsurface soil heat flux and independent measurements of soil water evaporation (i.e., the latent heat sink) are used to demonstrate this connection.

2. Materials and methods

2.1. Field site

Measurements were obtained at a field site located near Ames, IA (41°N, 93°W). Soil at the site is mapped as Canisteo silty clay loam (Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) with slopes ≤3%. Fall chisel plow tillage in combination with secondary tillage in the spring was used to prepare the field for planting prior to the experiments. Soil bulk density in the surface horizon was measured as 1.29 Mg m^{-3} post-tillage. Soybean was planted with 0.76 m row spacing on day of year (DOY) 131 in north-south oriented rows; emergence occurred on DOY 138-139. The measurement period discussed below occurred between DOY 142 and 161. Plant heights were determined on 2 days proximate to this period; heights were approximately 5.6 and 8.7 cm on DOY 152 and 159, respectively, based on an average of 209 plants each day. At this size, soybean root growth in the plant inter-row is considered minimal (cf. Mitchell and Russell, 1971). Because plants were small, the field site can be considered to be effectively bare. An adjacent long-term field study approximately 60 m from the instrumentation nest, within the same field, provided ancillary data including precipitation (tipping bucket gage), net radiation (four-component net radiometer; CNR 1, Kipp and Zonen, Delft, the Netherlands at 1.2 m above the soil surface), and soil water content at the 0–6-cm depth increment (Theta Probe Model ML2x, Dynamax, Inc., Houston, TX, USA).

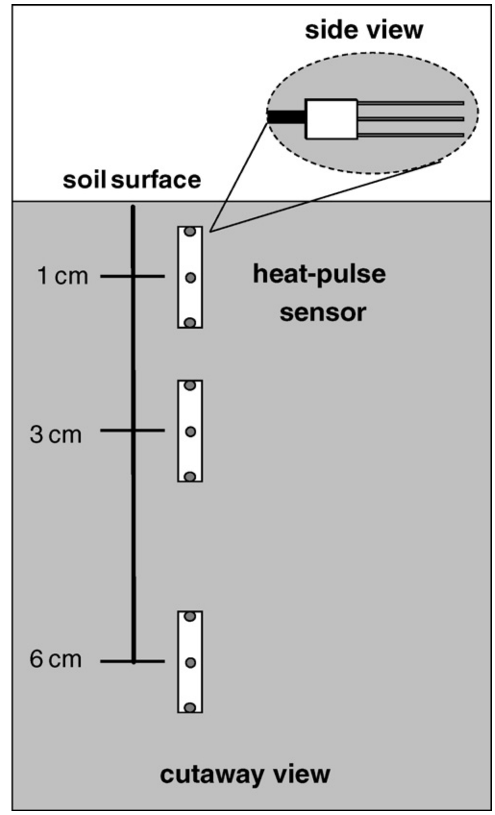

Fig. 1. Heat-pulse sensor installation. The cutaway view is drawn approximately to scale. The installation was repeated at three positions.

2.2. Heat flux measurements

Heat-pulse (HP) sensors built following the design of Ren et al. (2003) were used for soil heat flux measurement. The sensors consisted of three stainless steel needles (1.3 mm diam., 4 cm length) fixed approximately 6 mm apart with an epoxy body at one end. Each needle contained a Type E thermocouple for measuring temperature; the central needle also contained a resistance heater for generating a heat-pulse. The sensors were calibrated in agar stabilized water to determine the apparent distance between the needles (Campbell et al., 1991). The sensors were installed on DOY 140 via a 10 cm deep access trench by pushing the needles from the trench into undisturbed soil. HP sensors were installed at three depths in each profile, centered at 1, 3, and 6 cm, with the plane of the needles oriented perpendicular to the soil surface (Fig. 1). This installation was repeated at three adjacent locations (quarter row, mid row, and three-quarter row) for a total of nine sensors. After installation, the sensor lead wires were routed through the trench and the trench was carefully backfilled with soil. The sensors were connected to a data acquisition system on the soil surface,