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Experimental investigation of subsurface soil water evaporation on soil heat flux plate measurement

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HIGHLIGHTS

- Three methods of soil heat flux measurement were studied.
- Direct evidence of vapor transfer blockage with the plate method was provided.
- Needle-type sensors improved soil heat flux measurement accuracy.

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ABSTRACT

Accurate measurement of soil heat flux is required to describe the heat and mass transfer in soil. In this study, results of soil heat flux derived through the single probe and three needle gradient methods were compared with those obtained via the plate method. Field test was conducted on a bare loamy sand at 1-cm depth and a bare loam at 10-cm depth. Results from the two gradient methods revealed good agreement on flux measurement. The evaporation rate was relatively large on loamy sand, and the flux magnitude measured by the two gradient methods was 1.5 times higher than that of the plate method at 1-cm depth. However, the flux underestimation of the plate method was not observed at 10-cm depth of the bare loam in which the evaporation rate was negligible. Thus, the blockage of vapor transfer from the impervious plates primarily explained the heat flow divergence between the plate and gradient methods. Needle-type sensors exhibited a slight disturbance on the soil over the plate method, which may improve measurement accuracy. Heat flux plates must be placed relatively deep in the soil profile (e.g., 10 cm) to minimize measurement errors.

1. Introduction

Soil is a porous medium consisting of a mixture of minerals, organic matter, gases, liquids, and organisms that support plant life. Soil heat flux is a fundamental component of surface energy balance on earth. The accurate measurement of soil heat flux is required to characterize the transfer process of energy, water, and gas in the soil. The soil heat flux plate method has been the major method for measuring soil heat flux for decades [1]. This method embeds a thermopile in a thin disk with a fixed thermal conductivity, and the measured thermopile voltage output is converted into heat flux. However, potential errors of the plate method are recognized due to the construction of the impervious plate [1–5]. Ochsner et al. [1] discussed the potential errors of water vapor flow disruption in the impervious heat flux plate measurement. They hypothesized that water vapor movement and incidental latent heat transfer in the soil pore are not properly measured by the heat flux plate method. However, direct evidence that supports this hypothesis is lacking. Heitman et al. [6] demonstrated that the presence of a subsurface latent heat sink should be considered for an accurate determination of soil surface heat flux. Therefore, there exists a need to quantify the vapor flow and subsequent latent heat transfer in the heat flux plate measurement.

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A new heat pulse method was recently developed to measure subsurface soil evaporation at fine-scale depth increments [7,8]. The method can characterize vapor transfer in the depth of the soil heat flux plate measurement. In the present study, a single heat probe and a three needle heat pulse probe were used to compare with the heat flux plate method at various depths. The goal of this study is to provide experimental evidence of water evaporation occurring in the heat flux plate measurement depth. Using the independent measurements of soil evaporation at various depths, this study demonstrated that vapor transfer blockage produced by the impervious plate can readily explain the differences in subsurface heat flux measurement.

2. Experimental investigation

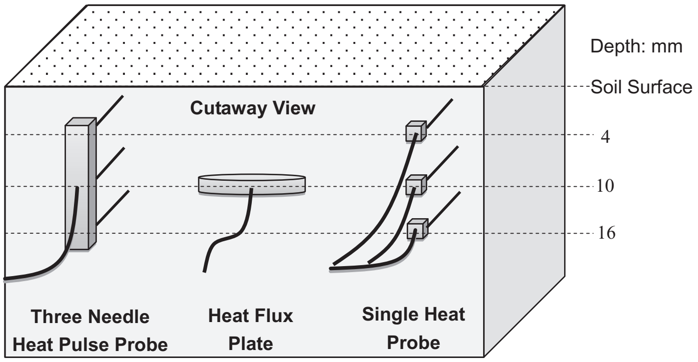
Three methods were used for soil heat flux measurements: a gradient method based on the single heat probe technique, a gradient method based on the three needle heat pulse technique, and the traditional soil heat flux plate method. Field experiments were performed on two lysimeters (a loamy sand lysimeter and a loam lysimeter) located at the experimental farm of China Agricultural University, Beijing (40° 01′ N, 116° 16′ E). This region has a semi-arid temperate climate with a mean annual precipitation of 600 mm. The altitude of the study site is 52 m above mean sea level, and the mean annual solar radiation is 5357 MJ m^{-2}.

There is no vegetation in the two experimental lysimeters. The volume of each lysimeter was $2 \times 2 \times 2$ m^3. Each lysimeter was packed with the sieved soil with a uniform soil bulk density. At the bare loamy sand lysimeter (79% sand, 13% silt, and 8% clay), the soil heat flux at 1 cm below soil surface was measured from September 16, 2011 to September 25, 2011 (see Fig. 1). At the bare loam lysimeter (47% sand, 29% silt, 24% clay), the soil heat flux at 10 cm below soil surface was measured from October 9, 2011 to October 16, 2011. During the installation of the single probe and three needle heat pulse sensors, a small trench was dug and the sensors were carefully inserted into the soil. In order to achieve a good soil-plate thermal contact, a horizontal groove slightly thinner than the plate thickness was created in the trench. Subsequently, the heat flux plate with an 80-mm diameter (HFP01, Hukseflux Thermal Sensors, the Netherlands) was carefully inserted into the groove. Three heat flux sensors were installed at the same depth with 10-cm spacing (Fig. 1). Finally, the trench was back-filled.

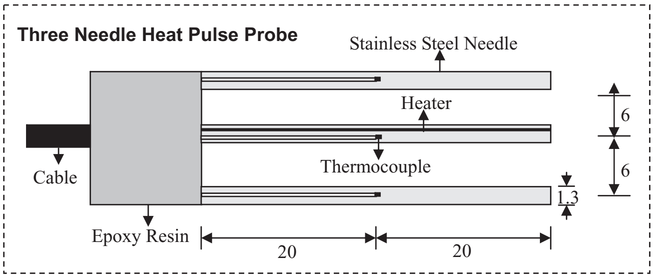
In the single probe gradient method, a single probe sensor with a diameter of 1.3 mm and a length of 40 mm was inserted horizontally in the soil trench (Fig. 1). A heater and temperature sensor of a thermocouple were mounted together in the single probe. Two thermocouple probes were installed 6 mm below and above the single heat probe to obtain the temperature gradient (Fig. 1). During the measurements, the probe temperature was recorded with a CR 23X datalogger (Campbell Scientific, Logan, UT) 60 s before heating, 60 s during heating, and 60 s after heating. Measured soil temperature rise was corrected with the ambient temperature drift according to the method of Jury and Bellantuoni [9]. Soil thermal conductivity was calculated using the analytical solution of the heat conduction equation [10]. To reduce the effect of probe thermal characteristics and contact resistance during the soil thermal conductivity calculation, the temperature data of 5–20 s immediately after the commencement of heating were excluded. Soil heat flux (H, W m^{-2}) was subsequently calculated by Fourier's law as follows [1,6–8,11,12]:

$$H = -\lambda \frac{dT}{dz} \tag{1}$$

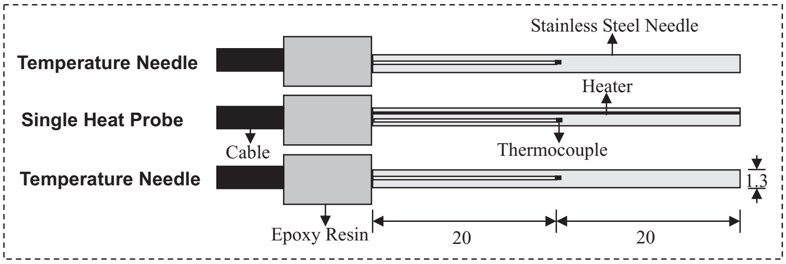
where λ is the soil thermal conductivity (W m^{-1} K^{-1}), T is the temperature (K), z is the soil depth (m), and dT/dz is the temperature gradient (K m^{-1}).



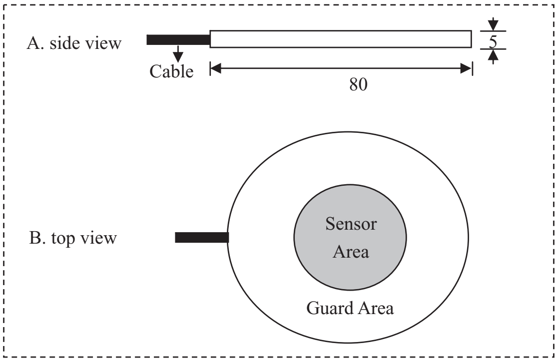
(a) Cutaway view of sensors installation



(b) Three Needle Heat Pulse Probe



(c) Single Heat Probe



(d) Heat Flux Plate

Fig. 1. Schematic view of (a) the heat flux sensors installation, (b) the three needle heat pulse probe, (c) the single heat probe and (d) the heat flux plate (not to scale). The dimensions are in millimeters.