Estimating soil heat flux using Distributed Temperature Sensing

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Abstract Often the smallest component of the surface energy balance, surface heat flux, is assumed to have low spatial variability. The standard measurement technique, which makes use of a heat flux plate, is thus considered to be appropriate. In this paper a method is presented to measure the spatial variability of surface heat flux. A custom-designed plough system deployed three fibre-optic cables at three different depths close to the soil surface. Distributed Temperature Sensing was then used to gather temperatures with a spatial and temporal resolution of 1 m and 30 seconds, respectively. These measurements clearly indicated large spatial variability in surface heat flux along a 70 m stretch. Variations of up to 100% between points 15 m apart could be observed. These results demonstrate the need for distributed soil heat flux measurements.

Key words soil heat flux; surface energy balance; spatial variability; Distributed Temperature Sensing, DTS

INTRODUCTION

Surface heat flux is an important component of the surface energy balance:

$$R_n = G + \lambda E + H \qquad (1)$$

where R_n (W/m^2) is net radiation, G (W/m^2) is surface heat flux, and λE (W/m^2) and H (W/m^2) are the latent and sensible heat fluxes. Most of the energy that enters the soil during the day leaves the soil during the night through terrestrial long-wave radiation. Therefore, G is often the smallest component in the daily surface energy balance. Sometimes G is even neglected, which can lead to large errors in the energy balance, especially in instantaneous or hourly estimates (Sauer *et al*., 2005). It is therefore important to be able to measure G accurately.

Furthermore, spatial variability in G is rarely considered. The standard method to measure G is with a soil heat flux plate. While using this method, one implicitly assumes that G does not vary greatly over space. Yet several studies have shown that spatial variation of G under field conditions can be significant (McCaughey, 1982; Ham & Kluitenberg, 1993; Tuzet *et al*., 1997; Kustas *et al*., 2000). Variation in G (measured at 0.08 m depth) between adjacent locations with similar cover in a dune with an uneven surface and partial shrub cover has been found to be greater than 200 Wm^{-2} (Sauer *et al.*, 2005). In order to analyse this spatial variability, simultaneous measurements of surface heat flux at multiple locations are necessary. In this paper we present a method to determine G in time and space over a large area with the use of Distributed Temperature Sensing (DTS) (Selker *et al*., 2006; Tyler *et al*., 2009; Sayde *et al*., 2010; Steele-Dunne *et al*., 2010). Since soil heat flux is a function of the change in temperature over depth, high resolution temperature measurements of the soil are a useful tool to determine soil heat flux.

METHODS AND MATERIALS

The study area for this research was an agricultural field on the Main Station Field Laboratory of the University of Nevada, Reno, USA (39º30′44″N, 119º42′56″W). The soil has a silt-loam texture and is covered with grass. Along a stretch of 100 m, three armoured two-fibre multi-mode 50/125 μ optic cables from Kaiphone Technology were installed under the soil surface. A custom designed cable plough was used to install the cables. The plough guides the cables through a blade that cuts through the soil under a 45 degree angle and leaves the cables at 1 cm, 6 cm and 11 cm depth. The blade cuts through the soil like a knife and soil disturbance is minimal. A Sensornet Sentinel DTS unit with a 4-channel Multiplexer Expansion Unit (Sensornet LTD, UK) was used. This DTS unit is suitable for use with cables up to 8 km long, can detect temperature variations of 0.01K at an integration time of 15 minutes, and has a maximal spatial resolution of 1 m. Air temperature, humidity, wind speed, and net radiation were measured at the site.

Thermal conductivity is dependent on moisture content, θ (-). In this case, moisture content is unknown and thermal conductivity has to be obtained from the relationship between diffusivity, $D(\theta)$ (m^2/s), conductivity, $K(\theta)$ (J/m·K·s), and heat capacity, $C(\theta)$ (J/K·m^3): $D(\theta)=K(\theta)/C(\theta)$.

Diffusivity can be calculated with the diffusion equation:

$$\frac{\partial T}{\partial t} = D(\theta)\frac{\partial^2 T}{\partial z^2} \tag{2}$$

with T as temperature (K), t as time (s), and z as depth (m). Heat capacity is a linear function of soil moisture:

$$C = n(1-S_r)\rho_a c_a + S_r n \rho_w c_w + (1-n)\rho_s c_s \tag{3}$$

where the subscripts a, w and s denote the air, water and soil solids, respectively, ρ (kg/m^3) is the density, c (J/kg·K) is the specific heat capacity, S_r (-) is the relative saturation and n (-) is the porosity and $\theta = n \cdot S_r$. Numerous models exist for the relationship between thermal conductivity and soil moisture. Here, the McCumber & Pielke (1981) model was used, with the Van Genuchten (1980) moisture/tension relationship, parameterized with the silt loam soil data provided by Al Nakshabandi & Kohnke (1965). Caution is needed regarding different relations between thermal conductivity and moisture content and moisture content and soil moisture tension because these relations are generally derived from rather small data sets. To obtain the thermal conductivity, first equation (2) is solved to obtain a diffusivity value for each location and each time step. The second step is to calculate the thermal conductivity and, finally, the moisture content can be determined with the use of the McCumber-Pielke model.

From the three temperature measurements along the cable, two layer-average heat fluxes can be calculated, one at 4.1 cm and one at 9.0 cm depth. Soil heat flux is proportional to the temperature change over the depth, according to $G_z = -K(\theta) \cdot dT/dz$. The fluxes at depths z are not equal to the surface heat flux (G_s). An additional term is needed to reflect the change in heat storage in the layer(s) between the surface and the depth of the calculated soil heat flux (G_z) (Mayocchi & Bristow, 1994). The surface heat flux equals the flux at depth plus the change in heat stored over time in the soil layer with thickness Δz: $G_s = G_z + S$ (Oke, 1987) with $S = C \cdot \Delta z \cdot dT/dt$. The method used here directly enables one to calculate this change in heat storage due to the presence of fibre-optic cables in the specific layers. This is an advantage over the conventional heat flux plate method, where additional thermometers are needed. The surface heat flux derived from the upper and lower soil heat fluxes should be similar in amplitude, but should have a small phase difference.

RESULTS

In Fig. 1, calibrated temperatures from the DTS measurements are presented for the middle cable (z = 0.06 m). The diurnal signal in temperature changes is clearly visible. Not shown here are temperatures at the other depths, but the data show a clear decrease in temperature amplitude with increasing cable depth. Temperatures in the upper cable range from –13.8°C to 18.6°C, while in the middle and lower cable the temperatures range from –13.6°C to 7.4°C and –12.5°C to 5.6°C, respectively. A distinct spatial variation along the cable is also visible. This variation can be due to differences in soil moisture, soil structure, or variation in cable depth.

The surface heat flux, calculated for the soil layer between the upper and middle cables, is plotted in Fig. 2. Values of the surface heat flux range from –147 W/m^2 up to 309 W/m^2. Two important different effects can be seen. First, as expected, there is an upward heat flux during the

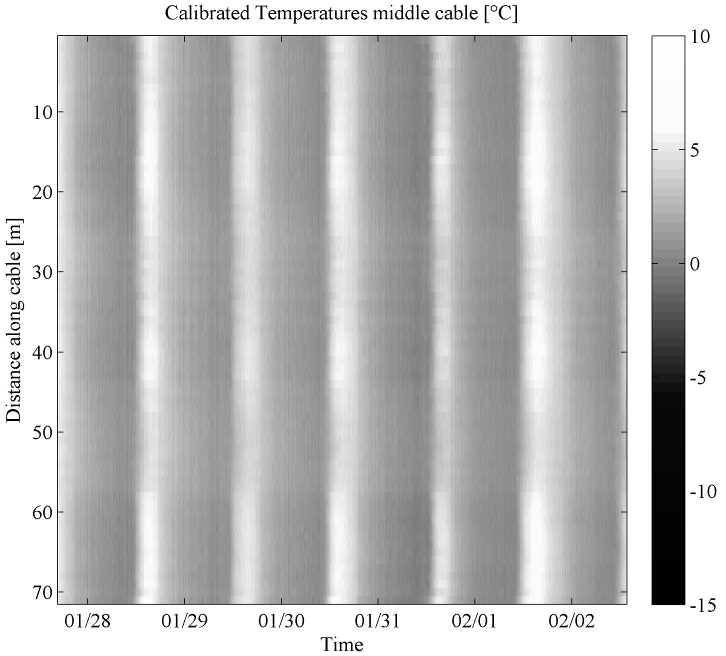

Fig. 1 Calibrated temperatures from the middle cable; the legend give temperatures in °C.

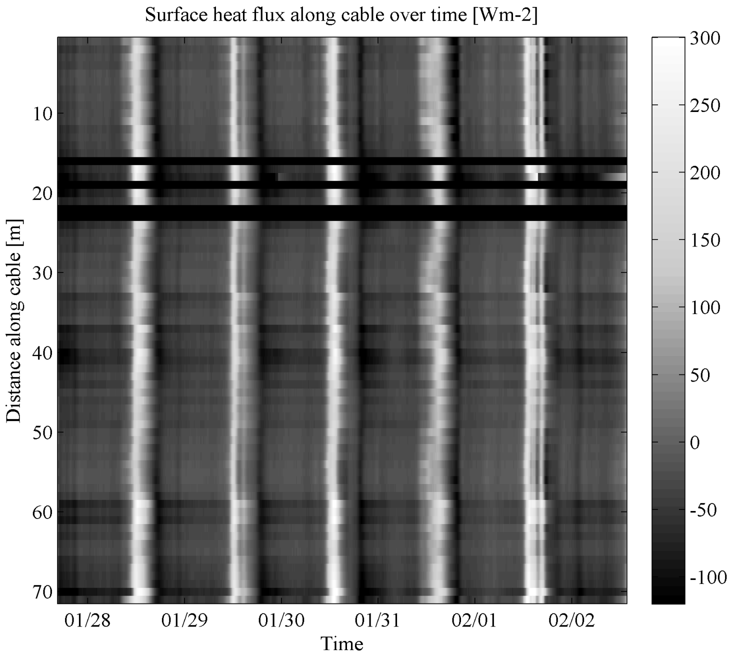

Fig. 2 Surface heat flux along the cable, the legend gives fluxes in W/m^2.

night changing to a downward heat flux during the day. Second, spatial differences in soil heat flux of up to 100% are found along the cable. The values for the surface heat flux during the day are relatively large compared to those found in the literature (Sauer *et al.*, 2005), as they are up to 30% of net radiation during the late morning. Differences of up to 100% can be found between points only 15 m apart, which is an indication of large spatial variability. The gaps in Fig. 2 (black horizontal lines at 17, 19, 22 and 23 m along the cable) are due to estimated diffusivity values that were outside the physical boundaries of the used model. On some points, no diffusivity could be fitted, which resulted in gaps in heat flux calculations.

The soil heat flux calculated from the temperatures of the upper and middle cable does not directly reflect the surface heat flux. The change in heat storage over time in the layer above the cables needs to be added to the heat flux at depth to obtain the surface heat flux. When the change in heat storage is not taken into account, errors of up to 100 Wm^{-2} can occur. The difference between the surface heat flux calculated from the lower soil heat flux estimate (Surface HF 2) and the upper soil heat flux estimate (Surface HF 1) can be seen in Fig. 3. The robustness of the overall method is demonstrated by the fact that the difference between the two is less than 10%.

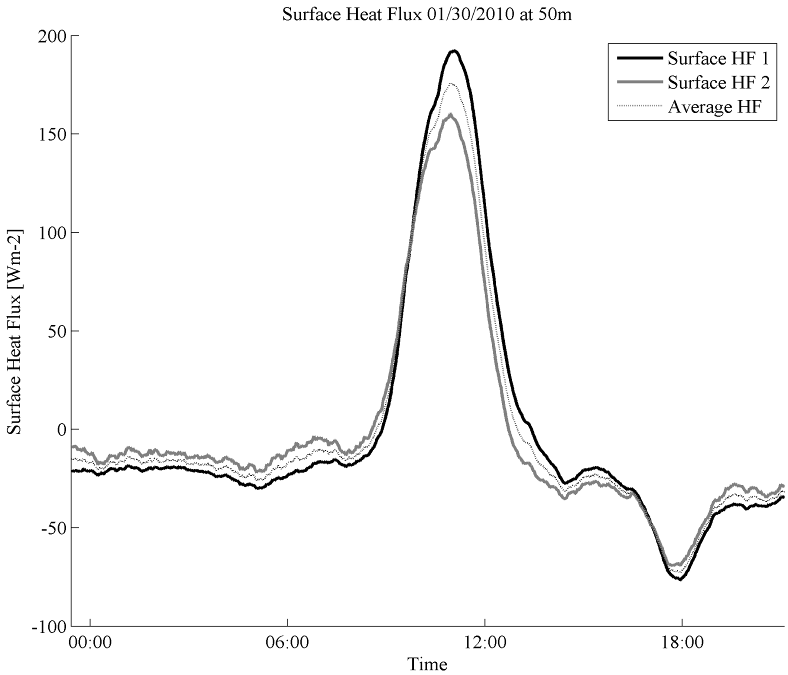

Fig 3 Surface heat flux as determined by the heat flux calculated by the top and middle cables (HF 1) and by the middle and bottom cables (HF 2).

DISCUSSION

The starting hypotheses of this paper were that spatial variability in surface heat flux may be significant and that DTS could be a useful tool to estimate this surface heat flux. The results show that, with the use of high resolution temperature measurements from DTS, a good estimate of surface heat flux can be made. Also, spatial variability was clearly visible in the results (Fig. 2). The cause of this spatial variation in surface heat flux remains to be investigated. As stated before, variations can be caused by differences in soil moisture, soil structure or cable depth. However, we do not know the extent to which each of these contributes to the variability.

Taking cable depth measurements into account (measurements not shown here), one can see that the pattern of cable depth variation is not similar to the pattern of spatial surface heat flux variation. A reasonable assumption is to expect a larger temperature amplitude and heat flux amplitude on locations where the cable is closer to the surface. Such heat flux characteristics were found at 20, 40 and 60 m. However, at 40 and 60 m the cable was roughly at its average depth and not very close to the surface. At 20 m some problems with unsteady cable depths occurred. These problems resulted in diffusivity values outside the physical boundaries of the McCumber Pielke model, which in turn resulted in blank spots in the surface heat flux calculations. In all, there is a strong indication that soil moisture is a dominant factor in spatially varying surface heat fluxes. Still, our method is strongly dependent on accurate cable depths. The way forward would be to work with longer time series with which the constant cable depths can be determined.

Surface heat flux was shown to be a significant part of the instantaneous energy balance, especially at the end of the morning. This paper shows spatial variability in surface heat flux of up to 100% within a 15 m span. The standard field technique to measure surface heat flux using heat flux plates can cause large errors due to significant spatial variability shown in this paper. Neglecting spatial variability can lead to significant errors when one tries to close the energy balance.

The spatial variability found in this paper occurred with a silt loam soil in a flat field. Similar studies will need to be performed on different soil types and topographies to see if such strong patterns occur elsewhere as well. To further reduce the influence of the cable on the soil characteristics it is advisable to conduct the same study after the cable has been in the ground for about a year, so the soil has time to "recover". For example, any cracks caused by the ploughing will then have disappeared and will no longer influence the measurements.

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