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Short communication

Using distributed temperature sensing to monitor field scale dynamics of ground surface temperature and related substrate heat flux

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ABSTRACT

We present one of the first studies of the use of distributed temperature sensing (DTS) along fibre-optic cables to purposely monitor spatial and temporal variations in ground surface temperature (GST) and soil temperature, and provide an estimate of the heat flux at the base of the canopy layer and in the soil. Our field site was at a groundwater-fed wet meadow in the Netherlands covered by a canopy layer (between 0 and 0.5 m thickness) consisting of grass and sedges. At this site, we ran a single cable across the surface in parallel 40 m sections spaced by 2 m, to create a 40 m × 40 m monitoring field for GST. We also buried a short length (≈10 m) of cable to depth of 0.1 ± 0.02 m to measure soil temperature. We monitored the temperature along the entire cable continuously over a two-day period and captured the diurnal course of GST, and how it was affected by rainfall and canopy structure. The diurnal GST range, as observed by the DTS system, varied between 20.94 and 35.08 °C; precipitation events acted to suppress the range of GST. The spatial distribution of GST correlated with canopy vegetation height during both day and night. Using estimates of thermal inertia, combined with a harmonic analysis of GST and soil temperature, substrate- and soil-heat fluxes were determined. Our observations demonstrate how the use of DTS shows great promise in better characterizing area-average substrate/soil heat flux, their spatiotemporal variability, and how this variability is affected by canopy structure. The DTS system is able to provide a much richer data set than could be obtained from point temperature sensors. Furthermore, substrate heat fluxes derived from GST measurements may be able to provide improved closure of the land surface energy balance in micrometeorological field studies. This will enhance our understanding of how hydrometeorological processes interact with near-surface heat fluxes.

1. Introduction

1.1. Importance of the land surface thermal regime

The thermal regime at the land surface is the result of the interactions between vegetation, soil and atmosphere (e.g. transpiration, evaporation, soil water- and heat transfer). These processes are affected by micro-topography, local hydraulic and thermal properties, and radiative and structure parameters, such as canopy height and leaf area index (e.g. Moene and van Dam, 2014; Rodriguez-Iturbe et al., 1999). These complex interactions can be formalized via the energy balance, which is closely related to the water balance via the evapotranspiration term. The energy balance describes how the net radiation received at the land surface, R_n, is distributed between evapotranspiration (latent heat flux, LE), sensible heat flux, H, and substrate heat flux, G_{sub}. The latter flux concerns heat that gets stored in (during the day) or released from (night-time) a substrate layer, consisting of topsoil and leaf-litter.

However, some researchers consider a skin layer heat flux (e.g. Holtslag and de Bruin, 1988; Steeneveld et al., 2006), where the skin layer consists of vegetation, within-canopy air space, leaf litter and top soil, with related effective temperature: the skin temperature. Following a Fourier-type heat transfer law, the skin layer heat flux depends on 'skin conductivity' and the topsoil-skin temperature gradient. Skin conductivity is a complex parameter, that is affected by soil/vegetation thermal properties, within-canopy temperature profiles (affecting canopy heat storage) as well as by within-canopy aerodynamic transfer.

The substrate heat flux, G_{sub}, more generally referred to as surface soil heat flux, as both litter layer and canopy layer are often ignored (in particular for short canopies), is a particularly

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important component of the land-surface energy balance under sparse or heterogeneous canopies. Whereas area-average estimates of the atmospheric fluxes (sensible and latent heat fluxes) can be reliably obtained from eddy covariance measurements, G_{sub} is commonly derived from a small number of point estimates, generally by using soil heat flux plates buried beneath the soil, combined with an estimate of heat storage above the plate, to yield an estimate of heat flux at the soil/substrate surface. Alternatively, G_{sub} can be determined from temperature measurements at or below the soil surface (e.g. Verhoef, 2004; Verhoef et al., 2012; van der Tol, 2012), as long as estimates of near-surface soil thermal properties are available. These temperatures are generally obtained using in-situ temperature probes installed (just) below the surface (e.g. Mayocchi and Bristow, 1995; Sauer and Horton, 2005). If leaf area index (LAI) varies considerably spatially, surface soil heat (substrate) flux estimates obtained at one or a few locations only may lead to poor energy balance closure ($R_n - G_{sub} \neq H + LE$), which is a widely observed phenomenon (Foken, 2008) that is not only caused by non-representative G_{sub} estimates, but can also be the result of atmospheric phenomena (e.g. advection).

The skin-, or land surface temperature (LST), plays a key role in all four energy balance fluxes. It is generally assumed to be a skin temperature to which the soil/litter layer (i.e. via the ground surface temperature, GST) and all canopy elements contribute, although with most of the signal coming from the top canopy layer. Quantifying the magnitude and spatial distribution of LST is important in micrometeorological and remote sensing studies, with the aim to further our understanding of the intricate functioning of natural or managed ecosystems. For example, through complex feedbacks the land surface thermal regime affects the spatial distribution of fauna and flora, and is a factor in controlling rates of primary production and biogeochemical processes. The spatial patterning of LST within a given habitat may provide thermal refugia for temperature sensitive species, enhancing the resilience of the ecosystem to short-term temperature maxima or minima (e.g. Ashcroft and Gollan, 2013).

LST can be monitored at the large scale using airborne thermal infrared techniques (e.g. Schmugge et al., 2002; Bertoldi et al., 2010). At an intermediate scale, ground based thermal infrared (IR) thermometers and cameras can be set up to monitor temperature variability over a scale of a few metres (Verhoef, 2004; Pfister et al., 2010), to hundreds of metres (Heinl et al., 2012). However, in the presence of a canopy layer, thermal IR imaging will only provide an effective skin temperature, with the uppermost canopy elements (e.g. sunlit top leaves) contributing most, so no explicit information on GST (i.e. at the base of the vegetation layer) will be available. Furthermore, LST, as well as GST, will be highly variable, in space as well as in time. To address this issue we need sensors that can measure temperatures in a spatially distributed and temporally near-continuous fashion.

Distributed temperature sensing (DTS) along fibre-optic cables, installed on the substrate surface or within the soil, provide a convenient means to obtain information on (the variability of) substrate and soil temperatures, e.g. for the verification of (below- and above-ground) multi-component soil-vegetation-atmosphere-transfer (SVAT) model outputs (e.g. Verhoef and Allen, 2000) for which separate measurements of vegetation and soil surface/substrate temperatures are required. Furthermore, line-averaged G_{sub} estimates, if the DTS temperature measurements are combined with measurements or estimates of thermal properties as mentioned above, would allow improved calculations of flux-partitioning when sensible heat flux is derived from scintillometry (Evans et al., 2012), whereas area-averaged estimates of G_{sub} (by using a horizontal multi-loop configuration) are more representative of flux tower footprint areas, and hence these are expected to lead to better energy balance closure than point-scale measurements with standard soil heat flux equipment. Hence, this paper aims to demonstrate the use of DTS technology in the determination of the spatio-temporal dynamics of soil- and near surface heat fluxes, and our purpose is not to advance the technology of DTS itself. As far as we are aware DTS has not been used for calculations of soil heat flux nor used to illustrate the implications of using a single measurement point as is practised widely in energy balance studies using a single heat flux plate (e.g. Wilson et al., 2002), to obtain soil heat flux for the determination of energy balance closure in heterogeneous canopies.

1.2. Distributed temperature sensing for monitoring ecosystem temperatures

Distributed temperature sensing (DTS) is being increasingly used for environmental temperature monitoring between the point and regional scale (e.g. Selker et al., 2006). DTS provides temperature measurements along an optical fibre at spatial intervals typically of around 1 m or less and temporal intervals of less than 1 min. The optical fibre can be configured into almost any spatial pattern such that a two- or three-dimensional space can be monitored for temperature from a single device. This approach, therefore has the potential to bridge the gap between point measurements which provide good temporal but poor spatial information, and remotely captured data which provide detailed spatial measurements but often poor temporal information. Furthermore, one continuous length of DTS cable can be partly placed on the soil and in the substrate, and within the canopy (at different heights, including near the canopy top to emulate IR-derived surface temperatures), thereby providing detailed information on GST and within-canopy temperature profiles, respectively.

The principle behind DTS is that a laser pulse is directed into a fibre optic cable and the intensity of backscattered photons arising from temperature dependent Raman scattering detected subsequently. Some photons return at higher frequencies, while others return at a lower frequencies. These are known as the anti-Stokes and Stokes intensities, respectively. The temperature, which more strongly affects the anti-Stokes signal, is computed from the ratio of these two intensities. For a more detailed explanation of the fundamental physical principles of the DTS method the reader is referred to Tyler et al. (2009).

A few examples exist of studies deploying DTS for monitoring temperature in natural or managed ecosystem applications. Krause et al. (2012) deployed DTS to investigate the extent to which invasive Rhododendron in a UK woodland modifies canopy temperatures. Similarly, Lutz et al. (2012) measured ground surface temperatures using DTS in both thinned and unthinned forests. In both cases the presence of a canopy was found to significantly moderate the ground surface temperature. These studies look at temperature along transects of cables; however, a two-dimensional configuration in the vertical was utilized by Thomas et al. (2011) to monitor atmospheric-surface layer flows by attaching the optical cable to a frame and system of pulleys. This type of approach (in the horizontal) is to our knowledge yet to be attempted for the monitoring of GST and the derivation of heat fluxes. To demonstrate how DTS can be used to map GST in relatively low canopies, how these temperatures are affected by canopy structure, and how such data can be used to obtain estimates of the spatiotemporal variation of substrate- and soil heat fluxes, we deployed a DTS system in a groundwater-fed meadow in the Netherlands.