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Validation of two soil heat flux estimation techniques against observations made in an engineered urban green space

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ABSTRACT

In highly developed landscapes, the soil heat flux that results from changes in land cover determines, in part, the extent to which urban climatic conditions can be modulated (e.g. retrofitting cities with new, engineered green spaces to reduce urban heat island effect). In this paper, temperature-dependent (TD) and temperature-independent (TI) soil heat flux models are validated against 6 days of measurements made in an engineered urban green space. The results suggest that the TI model (heat flux plate method) represents the observations better than the temperature-dependent one, which consistently overestimates soil heat flux at night and during the dusk-dawn period. Moreover, a sensitivity analysis reveals that the TD model is more sensitive to the selection of thermal conductivity and heat capacity values than the TI model. It can be concluded that the TI model is a more robust predictive tool, and especially in urban applications where soil properties may be highly uncertain.

Introduction

Soil (ground) heat flux (G) is the amount of thermal energy that moves through an area of soil over a unit of time, and is a key determinant of the temperature of the ground surface. Soil heat flux (SHF) is

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important in micrometeorology because it couples the energy transfer process at the surface (surface energy balance (SEB)) with the energy transfer processes at the soil (soil thermal regime) (Sauer and Horton, 2005). By helping to regulate soil temperature, SHF is also related to a range of important, temperature-dependent ecohydrologic processes, such as plant growth, biomass production, water uptake, evapotranspiration, and carbon assimilation.

The energy balance at the ground surface can be described through the following equation:

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

where R_n is the net radiation, G_0 is the ground (soil) heat flux, LE is the latent heat flux and H is the sensible heat flux. The left and right sides of the equation are often referred to as the available energy and turbulent fluxes, respectively.

Though it has been at times wholly omitted from some representations of the SEB, coarsely parameterized from basic meteorological parameters (e.g. as a fixed percentage of the net radiation), and measured with rather simple techniques (e.g. by using uncorrected heat flux plate measurements) (Liebethal et al., 2005), SHF can be the most important term in the energy balance equation (e.g. over dry bare soil). Ogee et al. (2001) discovered that within a forest, SHF could represent 30–50% of the net radiation occurring over the understory. Similar orders of magnitude have been computed for other types of vegetated land cover (Idso et al., 1975; Santanello, 2003). To our knowledge, no efforts to quantify SHF in urban green spaces have been performed, nor have any previously developed predictive models been validated in this context.

The goal of this study was to compare the ability of two previously-developed models of SHF- one temperature-dependent (Wang and Bras, 1999), and one temperature-independent (Wang and Bou-Zeid, 2012) to replicate SHF measurements made in a newly, engineered, urban green space. The study area was located in Queens, NY, USA and equipped with a SHF plate and soil sensors that measure both volumetric moisture content and soil temperature. Though field measurements at this site have been ongoing for more than a year, this study analyzed data for a six-day period during the summer of 2011. Two models and the experimental field site are described, followed by a statistical analysis of the goodness of fit and a sensitivity analysis of the two models.

Methodology

Two models were used to simulate data from the experimental field site. For each model goodness of fit was assessed from a series of statistical tests.

Half-order time derivative method (temperature dependent (TD) method)

Wang and Bras (1999) developed a half-order time derivative method to compute SHF from the 1D heat diffusion equation. Compared to previously proposed methods which require at least two layers of temperature data (Kimball and Jackson, 1975; Stull, 1988; Malek, 1993) only one layer of a soil temperature time series is necessary with the half-order time derivative method.

As stated above the half-order time derivative equation can be derived by combining the 1D heat diffusion equation for heat transport and Fourier's law in 1D, which states that for a homogenous entity, heat flux is proportional to the temperature gradient. With depth z increasing downward into the soil, heat transfer in a vertically homogeneous soil can be represented as by the following equation (Sellers, 1965):

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2} \tag{2}$$

where T is the soil temperature (K), z is a particular depth (m), t is time (s) and κ is the thermal diffusivity ($m^2\ s^{-1}$).

By assuming a uniform initial soil temperature profile and a constant fixed temperature at infinite depth, Eq. (2) can be solved using the following initial and boundary conditions:

$$T = T_0 \quad for\, t = 0, \quad z > 0, \tag{3}$$