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Forest understory soil temperatures and heat flux calculated using a Fourier model and scaled using a digital camera

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ABSTRACT

The characterization of the solar radiation environment under a forest canopy is important for both understanding temperature-dependent biological processes and validating energy balance models. A modified sinusoidal model of soil heat conductivity was used to estimate subsurface temperature and heat flux from the uneven but periodic solar heating of the soil surface due to sun flecks from a forest canopy. Using a mobile sensor platform with an infrared thermometer along an 11 m transect, a sunfleck model of soil surface temperature was tested using soil surface temperature maxima, air temperatures, and photodiodes placed on the soil surface to measure sunflecks. A pan-tilt-zoom digital camera on a 10 m tower above the site was then used to capture a time series of panoramic images of sunflecks reflected from the soil surface and to scale the sunfleck temperature model to a wide area. Finally, this image-based model of surface temperatures was combined with the modified sinusoidal model for heat conduction to estimate soil subsurface temperatures and heat flux over a wide area due to sunflecks from a forest canopy.

1. Introduction

Soil temperature strongly influences a wide range of biological, CO_2-producing processes including soil microbial activity and root metabolism and affects plant distributions on both large (e.g., Körner and Paulsen, 2004) and small scales (e.g., Schob et al., 2009). Measurements or estimates of soil temperature are also necessary components for estimating local and continental carbon and energy budgets and for calculating evaporative fluxes (Zheng et al., 1993; Gaumont-Guay et al., 2009). It has long been recognized that a variety of factors influence soil temperature, including climate, topography, above-ground vegetation, and soil physical characteristics (Balisky and Burton, 1995; Geiger et al., 2003). Because multiple factors influence soil surface heating, traditional *in situ* sensors may be inadequate for measuring the large spatial and temporal heterogeneity created by a forest canopy.

Most models for estimating soil temperature are based on simplified, bare-soil, or agricultural conditions (e.g., Gonzalez-Dugo et al., 2009; Saito and Simunek, 2009), although there are numerous efforts that include the influence of natural vegetation (e.g., Paul et al., 2004; Bond-Lamberty et al., 2005). Models for soil temperature and heat flux also vary in complexity from estimations of soil temperature based on readily available meteorological measurements (e.g., Weiss and Hays, 2005) to more complex and physics-based models requiring more specific measurements (e.g., Romano and Giudici, 2009).

Sinusoidal soil temperature models that assume periodic temperature fluctuations and are parameterized with simple meteorological measurements are particularly attractive due to their ease of calculation and minimal data requirements (Paul et al., 2004; Droulia et al., 2009). However, such models can provide unsatisfactory results because they assume soil homogeneity and ignore the spatiotemporal temperature variations caused by overstory shading (Hardy et al., 2004; Bond-Lamberty et al., 2005). A standard method of converting a complex signal into a set of more manageable sinusoidal signals is the Fourier transform, which when used in conjunction with sinusoidal heat conduction models, provides an elegant approach to modeling periodic but uneven subsurface soil temperatures (Van Wijk and de Vries, 1966).

Digital cameras and data storage have become increasingly affordable and hardware more easily integrated into systems for ecological data collection (Hamilton et al., 2007; Rundel et al., 2009). Image analysis from environmental studies, for instance for plant phenology detection, has primarily involved simple color transformations and analysis (Graham et al., 2009; Richardson et al., 2009). The application of digital cameras to the detection of sunfleck patterns on a soil surface requires similarly simple image processing procedures and can be analogous to that for detection of canopy parameters used in hemispherical canopy photography, a robust and well-documented method using a binary threshold-

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ing of images (Ishida, 2004; Cescatti, 2007). Where hemispherical canopy photography and its analysis can be concerned with predicting the amount of light that strikes the point at which the photograph was taken, a downwardly facing camera system that can recognize sunflecks on the soil surface can be used to monitor a much greater number of points over a large area but at the loss of the predictive power for each location.

Our objective was to combine a sunfleck model of soil surface temperature with a modified sinusoidal model for estimating subsurface soil temperatures to examine the effects of the uneven but periodic solar heating of the soil due to a forest canopy. The sinusoidal model was modified to better deal with subsurface soil heterogeneity. Because sunflecks can be captured as reflected light using a downwardly facing camera, a second objective was to spatially scale these models using a digital pan-tilt-zoom camera. Specifically, we first verified that a modified sinusoidal model could be used to predict subsurface temperature of an uneven but periodic surface temperature signal in the field. Next we constructed and tested a simple model of soil surface temperature based on sunfleck occurrence, maximum observed surface temperature, and air temperature. Then we applied the two models to a sequence of images captured of the soil surface under a forest canopy by a digital camera to spatially scale the soil surface and subsurface temperature estimates.

2. Materials and methods

2.1. Field site

The University of California James Reserve (www.jamesreserve.edu) is located in the San Jacinto Mountains of southern California (33°48′30″N, 116°46′40″W) at 1658 m elevation in a mixed conifer and hardwood forest with a perennial mountain stream. The area receives a mean of 485 mm precipitation annually. The area at which soil surface temperature measurements were taken is a forest gap 645 m^2 in area, as determined by the extent of the unobstructed view of the installed camera system. The middle of the gap has a site openness of 47%, as determined by the percentage of open sky seen from beneath a forest canopy using the analysis of a hemispherical canopy photograph (Gap Light Analyzer, Simon Fraser University, Canada).

Bulk density of the mineral soil, determined from 50 g samples taken just below the leaf litter at the James Reserve near the experimental transect within the forest gap was 1.21 ± 0.13 g m^{-3} ($n = 7$; mean ± SD). The soil in the bulk density samples was comprised of 77.5 ± 10.6% sand, 13.2 ± 6.1% clay, and 9.2 ± 4.8% silt, with 0.9 ± 0.6% organic matter contained within those fractions. During July, the soil was essentially dry from the surface to a depth of 8 cm. In March, the volumetric water content of the soil, measured by nearby dielectric sensors (EC-10, Decagon Devices, Pullman, WA, USA), was 0.02 m^3 H_2O m^{-3} at 2 cm and 0.09 m^3 m^{-3} at 8 cm; the average volumetric soil water content between the surface and 8 cm depth in March was estimated at 0.04 m^3 m^{-3}. In the laboratory, the volumetric heat capacity (C) and thermal conductivity (λ) were determined for dry soil from the site using the heat pulse method with home-built probes that were calibrated in both air and an aqueous gel with known C and λ, following Nusier and Abu-Hamdeh (2003). Both C and λ of a moist soil was then calculated from the values obtained from a dry soil ($C_{dry} = 1.41$ MJ m^{-3} $°C^{-1}$; $\lambda_{dry} = 0.62$ W m^{-1} $°C^{-1}$) by assuming that the apparent C and λ of any soil are due to the sum of separate values of the components of the soil, including the air and water fractions. Then, using the bulk density, we substituted the C and λ of air for that of water to 0.04 m^3 m^{-3} to determine for the moist soil C_{wet} of 1.60 MJ m^{-3} $°C^{-1}$.

2.2. Surface and subsurface measurement system

The networked infomechanical systems (NIMS) family of cable-based robotic systems, developed at the Department of Electrical Engineering, University of California, Los Angeles (UCLA), includes a rapidly deployable system (Jordan et al., 2007) that has been used for multiple environmental monitoring applications (Harmon et al., 2007; Caron et al., 2008; Graham et al., 2009). In this deployment, the NIMS system support cable was secured to two trees on the side of the forest gap and the motor control unit was attached to a wireless Ethernet bridge for remote control and programming of the system.

A surface scan of temperatures along the 11 m long NIMS transect involved moving the payload of sensors in 0.25 m increments, at which point the system dwelled for 30 s for sensor equilibration, then movement to the next location commenced. Data were captured continuously for 36 h for each measurement period by a datalogger (23X, Campbell Scientific, Logan, UT, USA). Data from a second datalogger (CR7, Campbell Scientific) connected to fixed sensors were collected simultaneously. Data were remotely archived in an open source database (MySQL Inc., Cupertino, CA, USA) with a custom front-end designed to facilitate the sharing of streaming sensor data (SensorBase, www.sensorbase.org; Chang et al., 2006).

Micrometeorological sensors on the NIMS shuttle included a downwardly facing infrared thermometer (Model 4000.3ZL, Everest Interscience Inc., Tucson, AZ, USA) to measure soil surface temperature. An emissivity of 0.9 was used for temperature conversion. Fixed sensors were clustered in four locations on the transect, at 1.75, 5, 7, and 9 m. Buried sensors included copper-constantan thermocouples (0.3 mm diameter) buried at 2, 8, and 16 cm depth and four self-calibrating heat flux plates (HFP01SC-L, Hukseflux Thermal Sensors B.V., Delft, The Netherlands) located at a depth of 8 cm. Depths refer to depths in mineral soil and do not include the thickness of the leaf litter layer, which were 3.2 ± 1.4 cm thick at position 1.75 m, 4.8 ± 2.6 cm at position 5 m, 3.9 ± 2.7 cm at position 7 m, and 2.6 ± 1.6 cm at position 9 m (values are mean SD; $n = 4$ at each location). Surface soil sensors included copper-constantan thermocouples and calibrated, upwardly facing gallium arsenide phosphide photodiodes (Hamamatsu, Bridgewater, NJ) in the same location as the buried sensors.

A dried and a wetted soil treatment were included within 3 m of the middle of the NIMS transect for energy balance comparisons (Qiu et al., 1998). Soil was previously excavated in approximately 10 cm layers to a depth of 0.5 m in an area without vegetation for each treatment and for the dried treatment each layer was spread on a plastic tarp and allowed to dry for 24 h. For both treatments, each layer was then sequentially placed into a rigid cylinder 30 cm in diameter and 36 cm deep that had an aluminum base to allow for vertical heat transfer through the cylinder (Qiu et al., 1998). Each layer was sequentially tamped down to approximate the original bulk density before excavating and a thin leaf litter layer, similar to the surrounding area, was spread over the soil surface of each treatment. Each treatment had a heat flux plate placed at 8 cm below the mineral soil and a thermocouple at 8 and 2 cm depths. An additional, stationary infrared thermometer was alternately placed approximately 20 cm above the soil surface to measure the temperature of each cylinder of soil during measurements made by NIMS.

2.3. Camera and image analysis

Images were captured using a pan-tilt-zoom (PTZ) networked video camera (Model VB-C50iR, Canon U.S.A., Lake Success, New York) mounted on a 10 m fiberglass tower at the James Reserve and connected to a local area network using Wi-fi. Images were collected at two different zooms, near maximum magnification