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Remotely sensed soil temperatures beneath snow-free skin-surface using thermal observations from tandem polar-orbiting satellites: An analytical three-time-scale model

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ABSTRACT

Subsurface soil temperature is a key variable of land surface processes and not only responds to but also modulates the interactions of energy fluxes at the Earth's surface. Thermal remote sensing has traditionally been regarded as incapable of detecting the soil temperature beneath the skin-surface. This study shows that thermal remote sensing can be used to estimate soil temperatures. Our results provide insights into thermal observations collected with tandem polar-orbiting satellites when used toward obtaining soil temperatures under clear-sky conditions without the use of any ground-based information or field-measured soil properties.

We designed an analytical three-time-scale (3-scale, for short) model, dividing the annual cycle of soil temperatures into three subcycles: the annual temperature cycle (ATC), which represents the daily-averaged temperature; the diurnal temperature cycle (DTC), which represents the instantaneous temperature; and the weather-change temperature cycle (WTC), which is divided into two parts to represent both the daily-averaged (WTC_{avg}) and the instantaneous temperature (WTC_{inst}). The DTC and WTC_{inst} were further parameterized into four undetermined variables, including the daily-averaged temperature, thermal inertia, upward surface flux factor, and day-to-day change rate. Thus, under clear-sky conditions, the four thermal measurements in a diurnal cycle recorded with tandem polar-orbiting satellites are sufficient for reconstructing the DTC of both land surface and soil temperatures. Polar-orbiting satellite data from MODIS are used to show the model's capability. The results demonstrate that soil temperatures with a spatial resolution of 1 km under snow-free conditions can be generated at any time of a clear-sky day. Validation is performed by using a comparison between the MODIS-inverted and ground-based soil temperatures. The comparison shows that the accuracy of inverted soil temperatures lies between 0.3 and 2.5 K with an average of approximately 1.5 K. These results open a new frontier in the application of thermal remote sensing wherein soil temperatures with high spatial and temporal resolutions can be remotely estimated.

1. Introduction

When the sun radiates energy onto a location on Earth, a portion of the absorbed solar radiation at the Earth's surface is conducted downward, changing the subsurface soil temperatures periodically at multiple temporal scales. Soil temperature within the shallow layers is an important variable for biophysicochemical soil processes, such as microbial activity, evaporation, aeration, seed germination, and root development (Hillel, 1998). Soil temperature from a relatively deep layer can be used to model land surface processes (Best, Cox, & Warrilow, 2005), to monitor subsurface urban heat islands and subsurface geothermal systems (Ferguson & Woodbury, 2007), and to optimally design underground pipes (Dalla Rosa, Li, & Svendsen, 2011).

Soil temperature can be obtained from both observations and models. Observed soil temperatures are usually measured by thermometers installed within the soil near the surface (e.g., the Soil Climate Analysis Network sites). These measurements are characterized by high accuracy, as well as high cost, but low representativeness over extensive and heterogeneous areas. Modeling has the advantage of providing the soil temperature at any depth and time. However, this

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approach requires the construction of equations that are capable of describing all of the possible physical processes in addition to a reasonable parameterization strategy for the soil parameters (such as the soil texture, pores, structure, water, fauna, organism interactions, and thermal properties), which is generally difficult in practice.

In spite of these challenges, soil temperature has been modeled for general planetary surfaces (Hapke, 1996; Yan, Chassefière, Leblanc, & Sarkissian, 2006) and for soil under a crop layer (Luo, Loomis, & Hsiao, 1992), a forest canopy (Bond-Lamberty, Wang, & Gower, 2005; Graham, Lam, & Yuen, 2010; Paul et al., 2004), or a snow cover (Hirota, Pomeroy, Granger, & Maule, 2002). Numerous methods have been proposed to simulate soil temperature, including numerical methods (Herb, Janke, Mohseni, & Stefan, 2008; Zoras, Dimoudi, & Kosmopoulos, 2012), analytical models (Lin, 1980), semi-empirical methods (Al-Temeemi & Harris, 2001; Droulia et al., 2009; Elias, Cichota, Torriani, & De Jong Van Lier, 2004), purely empirical methods (Zheng, Hunt, & Running, 1993), and statistical methods that employ intelligent algorithms, such as the neural network algorithm (Tabari, Sabziparvar, & Ahmadi, 2011). Numerical methods simulate the soil physical processes through the discretization of heat transfer (Langer, Westermann, Heikenfeld, Dorn, & Boike, 2013), and these methods can be adapted to complex urban environments in which heterogeneous soils containing multiple layers and irregular geometric structures are considered (Zoras et al., 2012). However, numerical methods require the use of many subsurface physical and chemical parameters and various meteorological variables that constrain the boundary conditions of soil heat conduction, resulting in weak extensibility. Analytical methods regularly use two approaches, including the Fourier equation (Carslaw & Jaeger, 1959) and the force-restore technique (Bhumralkar, 1975), to derive the soil heat flux and temperature. Such methods are suitable for parameterization and thus have been widely adopted in land surface models (Deardorff, 1978). Semi-empirical and empirical methods are easy to implement (Chow, Long, Mok, & Li, 2011) and provide an effective supplement for periods when there are no records of measured soil temperature due to unexpected instrument breakdown. Among these methods, special interest has been given to estimations of soil temperature based on the air temperature and other soil-temperature-related variables (Beltrami, 2001; Kang, Kim, Oh, & Lee, 2000; Smerdon et al., 2006; Zheng et al., 1993).

Although progresses have been made, obtaining soil temperatures over extensive areas remains a challenge due to the high heterogeneity of land surfaces (Zhan, Chen, Zhou, Li, & Liu, 2011). Thermal remote sensing is a promising technique to combat this challenge and has yielded credible land surface temperature (LST) products (Wan, 2008). However, satellite thermal sensors can only detect the skin-surface temperature to a depth of several micrometers (Kerr, 2007; Norman & Becker, 1995), and they cannot obtain subsurface thermal status directly with an instantaneous observation. Fortunately, there is more than one thermal measurement per daily cycle for most of the current LST products generated from tandem polar-orbiting sensors (e.g., the MODIS detects a majority of the Earth's surface four times per day) and geostationary satellite observations (e.g., SEVIRI-MSG provides thermal data at 15-minute intervals) (Rasmussen, Gottsche, Olesen, & Sandholt, 2011).

The multi-temporal sampling of LSTs has long been used to estimate the physical properties of soil (e.g., the thermal inertia and the correlated soil moisture) and the soil heat flux (Murray & Verhoef, 2007a,b). Progress in estimating soil physical properties based on satellite data has continued since the launch of the first generation of satellites in the 1970s (Kahle, 1977; Watson, 1975), with continuing improvements in the 1980s (Price, 1985), 1990s (Sobrino & El Kharraz, 1999; Xue & Cracknell, 1995), 2000s (Verhoef, 2004; Murray & Verhoef, 2007a), and 2010s (Zhan et al., 2012b). The physical properties of soils rather than soil temperatures have been the foci of these studies. Other research has attempted to estimate the soil heat flux by combining multi-temporal LSTs and limited knowledge of the surface or soil properties (Murray & Verhoef, 2007b; van der Tol, 2012; Verhoef, 2004; Verhoef et al., 2012; Wang & Bras, 1999). These studies require temporally quasi-continuous (e.g., sub-hourly) LSTs, which can be obtained from geostationary thermal observations.

However, the spatial resolution of geostationary observations is relatively low. Polar-orbiting thermal observations, possessing a spatial resolution several times higher, may be an alternative. The tandem arrangement of polar-orbiting satellites allows for the reconstruction of diurnal surface temperatures (Duan, Li, Wang, Wu, & Tang, 2012; Zhou, Chen, Zhang, & Zhan, 2013) and, thus, may indirectly detect the soil thermal status. Additionally, most previous investigations have attempted to incorporate the LSTs in a diurnal temperature cycle (DTC) but disregarded the full utilization of the LSTs in an annual temperature cycle (ATC), which are important for the estimation of relatively deeper soil temperatures. Therefore, an analytical method was developed to determine the soil temperature beneath the skin-surface. This process requires combining all the available LSTs in each DTC during an ATC, in addition to the visible and near infrared (VNIR) observations from polar-orbiting satellites.

This study follows the steps of using temporal thermal measurements to retrieve soil thermal properties and heat flux. We propose that the soil temperature under snow-free conditions can be estimated using satellite thermal observations. We believe that this approach can demonstrate the potential for satellite-based thermal observations to provide data that will complement and extend the current ground-based observation networks of soil temperature.

2. Problem and background

2.1. Problem

Both surface properties (e.g., land cover and surface geometry) and meteorological driving variables (e.g., air temperature) are required to determine the boundary conditions and, therefore, to drive the modeling of heat transfer. However, soil properties over extensive areas are highly heterogeneous. It is not easy to obtain both the soil properties at the pixel scale of satellite images and the climatic and meteorological status simultaneously. Satellite-observed multi-temporal LSTs result from the surface energy budget, and they already contain information on meteorological conditions. To determine the evolution of the upper boundary, we propose a three-time-scale model (3-scale, for short) to estimate soil temperatures using temporally sporadic satellite LSTs (see Sections 2.2, and 3.1 to 3.3). To determine the soil thermal properties, a method was constructed using samples collected from previous studies (see Section 3.4).

2.2. Background

Soil temperature dynamics are governed by multiple periodic or quasi-periodic cycles (see Fig. 1). Over a temporal scale longer than one year (e.g., decades), the annually averaged soil temperature at a specific site is constant in the absence of climate change. At a very short temporal scale (e.g., minutes), the soil temperature changes rapidly due to the downward conduction of surface heat, and the heat budget is further impacted by microscopic turbulence and horizontal advection (Meier & Scherer, 2012). The present study does not consider the aforementioned two scales because (1) the soil temperature variation due to the turbulence and advection can be weakened at the pixel scale, and (2) we only focus on estimating the annual and diurnal soil temperatures. Soil temperatures at depths greater than approximately 10 m (the actual depth at which the ATC has an impact depends on soil thermal properties and LST variations) barely change during an annual cycle (Schaetzl & Anderson, 2005); this depth was termed the zero annual range by Oke (1987). The aim of this study is to reconstruct the soil temperature profile between the skin-surface and the zero annual range, i.e., the soil temperature between 0 and approximately 10 m.

Within the zero annual range, several other cycles control the soil temperature dynamics. The diurnal temperature cycle (DTC) dominates