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A generic framework for modeling diurnal land surface temperatures with remotely sensed thermal observations under clear sky

Fan Huang [a], Wenfeng Zhan [a,b,*], Si-Bo Duan [c,d], Weimin Ju [a], Jinling Quan [b]

[a] Jiangsu Provincial Key Laboratory of Geographic Information Science and Technology, International Institute for Earth System Science, Nanjing University, Nanjing, Jiangsu 210093, China
[b] State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100875, China
[c] State Key Laboratory of Resources and Environment Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[d] University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

The modeling of diurnal land surface temperature (LST) is crucial to extend the temporally discrete satellite thermal observations in application to detect the surface property (such as thermal inertia) and fluxes (such as soil heat flux and evapotranspiration) that are important to climate change studies. This paper proposed a generic framework (GEM) for modeling the LST dynamics in clear-sky periods. This was performed by modeling the ground-surface heat flux, which was then transformed into temperature using the surface energy balance and heat conduction equation. Three terms of fluxes were incorporated into GEM, including the nonhomogeneous term depicting the approximate upward flux, the harmonic term representing the approximate solar radiation, and the residue term involving the surplus atmosphere-related flux variations. In a single diurnal temperature cycle (DTC), we derived seven cases of the GEM, i.e., from the GEM-I to -VII, in which two to twelve controlling parameters are required. These controlling parameters are taken as unknowns in backward inversion using temporally discrete surface temperatures. Validations were performed using in-situ brightness temperatures, and Moderate Resolution Imaging Spectroradiometer (MODIS) and Spinning Enhanced Visible and Infrared Imager (SEVIRI) LSTs. The results show that the accuracy generally increases from GEM-I to -VII, with the mean absolute error decreasing from 1.71 to 0.33 °C. Particularly, GEM-II and -III can be used to normalize the four MODIS LSTs in a DTC without additional information required; and GEM-VI and -VII are useful once high accuracy is required. Further modeling also indicates that GEM is capable of interpolating LSTs under nonstandard cases with arbitrary starting time, duration length, and local latitude. We consider this study could provide practitioners more options within particular applications for modeling the temperature dynamics under diverse requirements of modeling accuracy and controlling parameter number.

1. Introduction

Land surface temperature (LST) is a major determinant of terrestrial thermal behavior (Wan, Zhang, Zhang, & Li, 2002). Influenced by the surface–atmosphere interactions, the LST also modulates this process and accordingly the related energy fluxes (Sandholt, Rasmussen, & Andersen, 2002). Satellite thermal remote sensing, via receiving the longwave radiation aggregated from large-scale land surfaces, probably provides the only technique to obtain regular LSTs over extensive areas. However, this technique suffers from the tradeoff between the spatial and temporal resolutions (Zhan et al., 2013). Associated with this tradeoff is that all thermal sensors onboard satellites, e.g., the polar-orbiting and geostationary sensors in particular, sample the surface in a temporally discrete fashion. Based on these discrete LSTs, investigations have been performed on modeling LST dynamics, by which the surface and even subsurface properties can be derived (Cracknell & Xue, 1996; Zhan et al., 2014; Zhao et al., 2012) and the atmospheric status can be inferred (Watson & Hummer-Miller, 1981). The modeling of diurnal LST dynamics contributes to the compression of data amount within geostationary LSTs (Göttsche & Olesen, 2001). It has additional potential to help normalize satellite LSTs obtained at different times of day (Coops, Duro, Wulder, & Han, 2007; Duan, Li, Tang, Wu, & Tang, 2014) and to predict crop yields (Lobell, 2007).

1.1. Literature review

The modeling of LST dynamics using thermal observations has advanced greatly in recent decades. Interestingly, the earliest method of its kind was developed not for the earth but for the moon (Jaeger, 1953; Wesselink, 1948), mostly because the moon can be remotely

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* Corresponding author at: No. 163 Xianlin Avenue, Qixia District, Nanjing, Jiangsu 210046, China. Fax: +86 25 89681030.
E-mail addresses: nju_huangfan@163.com (F. Huang), zhanwenfeng@nju.edu.cn (W. Zhan), duansibo@gmail.com (S.-B. Duan), juweimin@nju.edu.cn (W. Ju), jlquan0123@gmail.com (J. Quan).

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sensed on the earth but the earth surfaces cannot be remotely observed until the launch of man-made satellites, the first of which appeared in the late 1950s. Methods on modeling diurnal temperature cycle (DTC) can be divided into four categories: (1) the physical method, (2) the quasi-physical (or thermal inertia based) method, (3) the semi-physical (or semi-empirical) method, and (4) the statistical method. Note that among these methods of four categories, sometimes no strict line exists.

The physical method, characterized by its high complexity, tries to model the DTC using high-accuracy surface properties (e.g., surface geometry, albedo, and thermal diffusivity) and meteorological variables on wind, air temperature, humidity and pressure, which are measured by satellites or ground meteorological stations. Most land surface models (LSMs) such as the Biosphere–Atmosphere Transfer Scheme (Dickinson, Kennedy, & Henderson-Sellers, 1993) should be categorized as the physical method. The LSMs are complicated and the surface temperature is just one of the physical parameters (e.g., soil moisture, heat flux, and temperature) modeled by the inputs (i.e., surface properties and meteorological variables). By combining the associated meteorological measurements, simplified versions of the LSM were also developed to produce thermal inertia and to model the LST variation (Kahle, 1977).

The quasi-physical method relates DTC to the thermal inertia of land surfaces and several composite coefficients that reflects the upward flux, which is a combination of the surface-emitted longwave radiation and sensible and latent heat flux. It is directly based on the surface energy balance (SEB) to derive the dynamics of surface temperature. Intended for geologic mapping or soil moisture monitoring, a majority of these methods were initially designed to invert thermal inertia using the day–night LSTs from geostationary or polar-orbiting satellites (Cracknell & Xue, 1996). With the calibrated thermal inertia, the DTC can then be reconstructed. The quasi-physical method assumes that the shortwave net radiation follows a half-wave shape. To obtain an analytical solution given by Carslaw and Jaeger (1959), many studies further assume that the upward flux can be parameterized as a linear function of LST (Cracknell & Xue, 1996; Pratt, Foster, & Ellyett, 1980; Price, 1977; Sagalovich, Fal'kov, & Tsareva, 2002; Sobrino & El Kharraz, 1999a, 1999b; Watson, 1975, 1982, 2000; Xue & Cracknell, 1995). Recent developments include the assimilation of easily-obtained air temperatures to compensate the linearized boundary condition and therefore improve the modeling of DTC for urban facets (Zhan et al., 2013).

The semi-physical method directly makes assumptions on the temperature wave rather than ground-surface heat fluxes and it models the DTC with several external temperature related parameters that are implicitly linked to the surface property (e.g., temperature amplitude) and atmospheric status (e.g., residual temperature and total optical thickness) (Göttsche & Olesen, 2009). The semi-physical method continues to simplify the DTC process that a harmonic temperature wave dominates the period subsequent to sunrise, which is followed by an exponential Newton-type of cooling starting usually in the afternoon (Parton & Logan, 1981). Two piecewise functions are then used to graph the harmonic and exponential periods. A most representative method of this kind is from Schädlich, Göttsche, and Olesen (2001) and Göttsche and Olesen (2001), which was later enhanced to consider the asymmetry of the daytime harmonic period (van den Bergh, van Wyk, van Wyk, & Udahemuka, G. 2007), to optimize the parameter estimation (Jiang, Li, & Nerry, 2006), to better represent the cooling period using hyperbolic rather than exponential functions (Inamdar, French, Hook, Vaughan, & Luckett, 2008), and to better characterize day-to-day temperature evolutions (Duan et al., 2013). Lately this method was also advanced by incorporating the atmospheric optical thickness to overcome the inaccuracy at around the sunrise (Göttsche & Olesen, 2009). The aforementioned DTC methods were evaluated recently and the results confirm that acceptable accuracy is achieved by all these methods (Duan, Li, Wang, Wu, & Tang, 2012). There is also another category of semi-physical DTC methods using the harmonic rather than exponential functions to depict the nighttime cooling (Jin & Dickinson, 1999; Sun & Pinker, 2005). This strategy was shown feasible because, from a climatic perspective, monthly mean other than instantaneous temperatures are the focus in these studies.

The statistical method, namely the data-driven method (van den Bergh et al., 2007), is another group of methods for modeling DTC. No physical rendering relating to the SEB or heat conduction equation (HCE) is used. The statistical method reconstructs the DTC through a statistical analysis of the measured surface temperature (Aires, Prigent, & Rossow, 2004) or its relationship with local information on geolocation (Coops et al., 2007). The key of these methods relies on the integration of multisource data, which provide a sample basis for statistical analysis used for temperature interpolation. The principal component analysis is the most widely used technique to retrieve diurnal patterns of surface temperatures and earlier studies show the first two or three components are sufficient for such representations (Aires et al., 2004; Ignatov & Gutman, 1999; Zakšek & Oštir, 2012). In addition, simple regressions between LST and the related parameters, e.g., image acquisition time, local geolocation, and altitude, are shown feasible to generate wide-range diurnal LSTs with the Moderate Resolution Imaging Spectroradiometer (MODIS) LST product (Coops et al., 2007; Crosson, Al-Hamdan, Hemmings, & Wade, 2012).

Among these four categories, the quasi- and semi-physical methods are more popular than the other two in remote sensing. This is because these two can be easily driven by temporally discrete thermal observations. From the 1970s to 2000, the quasi-physical method prevailed due to the launch of a series of airborne and spaceborne thermal sensors (or satellites) including Nimbus, Heat Capacity Mapping Mission (HCMM), Advanced Very High Resolution Radiometer (AVHRR), and MODIS. In comparison, the semi-physical method becomes prevalent especially in the recent decade starting from 2000, mostly due to its simplicity and regard of both physical rendering and suitability of being driven by remote sensing data.

1.2. Problems

Albeit great progresses were made on the semi-physical method, unsettled problems remain. First, it assumes that only one sunrise and one sunset occur during a diurnal cycle (Göttsche & Olesen, 2001). The dissatisfaction of this condition invalidates the assumption that a DTC is comprised of a harmonic temperature wave followed by an exponential cooling. Second, a diurnal cycle may not be necessarily defined between two sunrises. Methods fail when LSTs need to be interpolated freely in the temporal domain with an arbitrary duration length. Third, although the day-to-day progression at the transition moment (i.e., the continuity between two adjacent days) was considered (Duan et al., 2013), the continuity of the first derivatives of the two piecewise functions was disregarded. Finally, practitioners have few options when facing data with different numbers of thermal observations in a DTC. This is because the modeling accuracies of the semi-physical methods are similar, with the accuracy incapable of being further promoted if adequate number of measurements is at hand.

This paper tries to solve these problems based on the strategy used by the quasi-physical method. Although characterized by a higher complexity, the quasi-physical method is more resilient than most semi-physical methods simply because it is directly derived from the SEB. First, the parameterization on ground-surface heat flux rather than directly on LST benefits the quasi-physical method under nonstandard cases illustrated in the first and second problems. Second, this indirect parameterization automatically overcomes the continuity problem through the analytical solution of the heat conduction. Third, the quasi-physical method is based on parameters such as thermal inertia and daily average temperature. These two parameters directly relate to the surface property and atmospheric status, respectively. This advantage facilitates the method extension under few thermal