ISPRS Journal of Photogrammetry and Remote Sensing 142 (2018) 190–204

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Comprehensive assessment of four-parameter diurnal land surface temperature cycle models under clear-sky

Falu Hong[a], Wenfeng Zhan[a,b,*], Frank-M. Göttsche[c], Zihan Liu[a], Ji Zhou[d], Fan Huang[a], Jiameng Lai[a], Manchun Li[a]

[a] Jiangsu Provincial Key Laboratory of Geographic Information Science and Technology, International Institute for Earth System Science, Nanjing University, Nanjing, Jiangsu 210023, China

[b] Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing 210023, China

[c] Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

[d] School of Resources and Environment, Information Geoscience Research Center, University of Electronic Science and Technology of China, Chengdu, Sichuan 610054, China

ARTICLE INFO

Keywords:
Land surface temperature
Diurnal temperature cycle
Polar-orbiting satellite
Thermal remote sensing
Model comparison

ABSTRACT

Diurnal land surface temperature cycle (DTC) models are useful tools for generating continuous diurnal land surface temperature (LST) dynamics from temporally sparse satellite observations. Four-parameter DTC models (FPD) can be applied to tandem polar-orbiting satellite observations that sample the surface at least four times per day and, therefore, they have received especial attention. Different approaches have been proposed to reduce the parameter number of DTC models to only four, but a comprehensive and systematic comparison of the published FPDs and their performance is lacking. In addition, it remains unclear whether there are even better parameter-reduction approaches (PRAs) for DTC modeling when only four observations per day are available. Consequently, we chose three semi-empirical DTC models (GOT01, INA08, and GOT09) and one quasi-physical DTC model (GEM) and obtained nine FPDs with PRAs (e.g., by fixing some of the DTC parameters as constants). Using *in-situ* thermal observations from the U.S. Climate Reference Network, as well as LSTs from the geostationary MSG and FY-2F satellites under clear sky, we compared the performances of these nine FPDs for 24 and 4 available LST observations per day. We obtained the following results: (1) The GOT09- and GEM-type models generally performed better than the other models with *in-situ* measurements, while the INA08-ts and GOT09-type models possessed high accuracies for the geostationary LSTs. (2) For the semi-empirical models, the PRA '$t_s = t_{ss} - 1$' (where t_s and t_{ss} are the onsets of nighttime cooling and sunset, respectively) is generally more accurate than the PRA '$\delta T = 0$' (where δT is the day-to-day change of residual temperature). The only exception is the GOT09-type model, for which the '$t_s = t_{ss} - 1$' strategy is less accurate. (3) GOT09-dT-τ, which fixes δT as zero and the atmospheric optical thickness (τ) as 0.01 for parameter reduction, shows the best performance of the FPDs. The study gives an overview of commonly-used four-parameter DTC models, provides a foundation for generating spatio-temporally continuous LST products, and offers guidance for choosing four-parameter DTC models in various applications.

1. Introduction

As one of the key parameters of land-atmosphere energy exchange, land surface temperature (LST) has been widely used in various disciplines, including meteorology and climate, hydrology, and ecology (Anderson et al., 2008; Karnieli et al., 2010; Qiao et al., 2013; Wan and Li, 1997; Weng, 2009). Compared with traditional *in-situ* measurements, satellite thermal remote sensing has become increasingly attractive because of its ability to obtain LSTs regularly over an extensive region. However, there is a tradeoff between the spatial and temporal resolutions of most satellite observations, which results in a temporally discontinuous or even sporadic sampling of the surface and hinders the retrieval of continuous LST fields. Fortunately, the temporally continuous LST dynamics can be reconstructed using diurnal temperature cycle (DTC) models. By assisting the generation of temporally continuous LSTs, DTC models (or diurnal LST dynamics) have demonstrated their value for the retrieval of LST and emissivity (Jiang et al., 2006), reconstruction of spatio-temporally continuous and/or

* Corresponding author at: Nanjing University at Xianlin Campus, No. 163, Xianlin Avenue, Qixia District, Nanjing, Jiangsu Province, 210023, China.
E-mail addresses: hongfalu@foxmail.com (F. Hong), zhanwenfeng@nju.edu.cn (W. Zhan), frank.goettsche@kit.edu (F.-M. Göttsche), rs312lzh@yeah.net (Z. Liu), jzhou233@uestc.edu.cn (J. Zhou), nju_huangfan@163.com (F. Huang), NJULJM@126.com (J. Lai), manchun@nju.edu.cn (M. Li).

https://doi.org/10.1016/j.isprsjprs.2018.06.008
Received 10 January 2018; Received in revised form 29 April 2018; Accepted 10 June 2018
0924-2716/

consistent LSTs (Duan et al., 2014a; Göttsche and Olesen, 2001; Holmes et al., 2016; Inamdar et al., 2008; Liu et al., 2017), estimation of LST under cloudy condition (Zhang et al., 2015), downscaling/disaggregation of LSTs (Quan et al., 2014; Zhan et al., 2016), estimation of surface air temperatures (Bechtel et al., 2014, 2017; Gholamnia et al., 2017; Zakšek and Schroedter-Homscheidt, 2009), derivation of surface thermal properties (Holmes et al., 2015; Sobrino and El Kharraz, 1999), temporal extrapolation of surface fluxes (Hain and Anderson, 2017), and the monitoring of diurnal surface urban heat islands (Weng and Fu, 2014; Zakšek and Oštir, 2012; Zhou et al., 2013).

Among the DTC models, the quasi-physical model (QPM) and semi-empirical model (SEM) are the two prevalent categories (Huang et al., 2014). Using heat flux as the key variable, the QPM acquires the LST dynamics formula by parameterizing the surface flux components within the surface energy balance equation (Cracknell and Xue, 1996; Huang et al., 2014; Price, 1977; Sobrino and El Kharraz, 1999; Xue and Cracknell, 1995; Zhan et al., 2014). The QPM is relatively complex and its parameter number may range from two to twelve. By comparison, the SEM describes LST dynamics directly using LST as the key variable, and models its dynamics by empirical functions (Göttsche and Olesen, 2001, 2009; Inamdar et al., 2008; Parton and Logan, 1981; Sun and Pinker, 2005; Van Den Bergh et al., 2007). The structure of the SEM is generally relatively simple and its parameter number typically ranges from three to six.

There is a tradeoff between modeling accuracy and the parameter number of DTC models. DTC models with more parameters usually possess higher accuracies (Duan et al., 2012; Huang et al., 2014), but are usually less applicable to satellite LST with a relatively low temporal resolution, e.g., when there are fewer daily overpasses than free model controlling parameters (Duan et al., 2014b). In contrast, DTC models with fewer parameters usually reproduce the input data with lower accuracy, but they are better suited to modelling satellite data with fewer daily overpasses (Huang et al., 2014; Watson, 2000).

DTC models were initially applied to hourly or sub-hourly thermal data from geostationary satellites with relatively coarse spatial resolutions (around 3–5 km). Such a coarse resolution, however, greatly limits the applications that require fine-scale thermal data for the surfaces (Duan et al., 2014b; Inamdar et al., 2008). LST products obtained by tandem polar-orbiting satellite systems (e.g., AVHRR and MODIS) can provide four overpasses per day, have a finer spatial resolution (around 1 km), complement the coarse geostationary LSTs, and have been widely used in related applications (Imhoff et al., 2010; Vancutsem et al., 2010; Wan et al., 2004). But with only the four transits within a diurnal cycle, important features on the diurnal variations of specific applications (e.g., for monitoring of urban heat islands) may be missed (Duan et al., 2014a; Zakšek and Oštir, 2012). Consequently, four-parameter DTC models (hereafter termed FPDs) have received especial attention, since they can fully reconstruct diurnal LST dynamics with only four observations (Duan et al., 2014b). The FPDs have demonstrated their utility for many applications requiring full DTC information: e.g., the timing of daily maximum LST, estimation of diurnal mean LST and diurnal LST range, and retrieval of surface thermal inertia (Holmes et al., 2013; Sobrino and El Kharraz, 1999; Zhan et al., 2014).

Due to their usefulness, great progress has been achieved in developing FPDs. Generally, FPDs can be divided into two categories: The first focuses on reducing the parameter number of the DTC models to four, by fixing one or more of their parameters as constants for individual cases. For example, Schädlich et al. (2001) assumed that the day-to-day change of residual temperature (i.e., δT) of semi-empirical DTC models approximates to zero in simple cases; Holmes et al. (2013) suggested that the start of the attenuation function (termed t_s) can be equated to the time when the temperature has decreased to half its maximum value; and Duan et al. (2014b) proposed that t_s is often exactly one hour before sunset (t_{ss}). Similarly, by the parameterization of the upward surface fluxes, FPDs can be directly derived from quasi-physical model DTC models (Huang et al., 2014; Sobrino and El Kharraz, 1999; Zhan et al., 2014). For the second FPD category, DTC models with more than four parameters are solvable using only four daily observations when additional information (e.g., from the temporally or spatially adjacent LST pixels) is incorporated. The additional information/knowledge can be the monthly LST dynamics obtained from land surface models, or geostationary LSTs that provide a background field for solving DTC models (Aires et al., 2004; Jin and Dickinson, 1999; Sun and Pinker, 2005; Zhou et al., 2013); day-to-day temperature continuity within a multi-day period (Duan et al., 2013); or the consistency of component temperature dynamics within neighboring pixels (Quan et al., 2014).

In addition to the temporal continuum or spatial consistency hypothesis, the second category of FPDs is relatively complex and may induce additional uncertainties caused by the ancillary data used for derivation of component information. By contrast, the structure of the first category of FPDs is relatively simple, and they can be operated based on LST data within a single day for a single pixel. In other words, the first category of models has the advantage to be implemented more easily and can therefore be more suitable for related applications. Previous parameter-reduction approaches (PRAs) were only tested on a single specific DTC model. The reduced parameters as shown (e.g., δT and t_s) appear in most of the five-parameter semi-empirical DTC models including GOT01 (Göttsche and Olesen, 2001) and INA08 (Inamdar et al., 2008), as well as the six-parameter semi-empirical DTC model GOT09 (Göttsche and Olesen, 2009). Therefore, these two PRAs can be applied to all these models. In addition, the parameter number of the QPM can be adjusted to four if specific parameterization schemes are used (Huang et al., 2014; Zhan et al., 2014).

With suitable PRAs, it is expected that several FPDs can be generated; however, several challenges remain for these potential models: First, a comprehensive assessment of the performances of these potential FPDs is lacking; and second, it remains unclear whether there exist PRAs that are able to generate FPDs with even higher accuracies. To address these issues, the present study aimed to compare both the hourly and overall performances of the FPDs, and further to identify the best FPDs under different cases. Our study is based on several *in-situ* thermal measurements within very different biomes, as well as LSTs retrieved from geostationary satellites across an extensive scale. Our findings are potentially useful for selecting FPDs for practical applications, and for the generation of temporally continuous LST data from four overpasses in a daily cycle; thus, they are also potentially useful for related applications.

2. Data

To cover as many land cover types across the globe and to use as many data sources under various bioclimates as possible, we incorporated both *in-situ* surface temperatures and LSTs obtained from geostationary satellites (Fig. 1). The *in-situ* LSTs were collected by the United States Climate Reference Network (USCRN) (Fig. 1a), while the LSTs were retrieved by the Land Surface Analysis Satellite Application Facility (LSA SAF) from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard Meteosat Second Generation (MSG), operated by the European Organisation for the Exploitation of Meteorological Satellites (Fig. 1b), as well as by the FengYun-2F (FY-2F), operated by the Chinese Meteorological Administration National Satellite Meteorological Center (Fig. 1c).

2.1. *In-situ measurements*

We chose the *in-situ* measurements from the USCRN because this network contains surface cover types with a sufficient number of varieties spanning very different bioclimates. The USCRN provides observations of most of the basic meteorological variables at 5-minute intervals, including air temperature, LST, wind speed, and relative humidity. The 5-minute LST data (i.e., 288 observations in a single day)