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Effect of emissivity uncertainty on surface temperature retrieval over urban areas: Investigations based on spectral libraries

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ABSTRACT

Land surface emissivity (LSE) is a prerequisite for retrieving land surface temperature (LST) through single channel methods. According to error model, a 0.01 (1%) uncertainty of LSE may result in a 0.5 K error in LST under a moderate condition, while an obvious error (approximately 1 K) is possible under a warmer and less humid situation. Significant emissivity variations are presented among the anthropogenic materials in three spectral libraries, which raise a critical question that whether urban LSE can be estimated accurately to meet the needs for LST retrieval. Methods widely used for urban LSE estimation are investigated, including the classification-based method, the spectral-index based method, and the linear spectral mixture model (LSMM). Results indicate that the classification-based method may not be effectively applicable for urban LSE estimation, due mainly to the insignificant relation between the short-wave multispectral reflectance and the long-wave thermal emissivity shown by the spectra. Compared with the classification-based method, the LSMM shows relatively more accurate predictions, whereas, the performance of the LSMM largely depends on the determination of endmembers. Obvious uncertainties in LSE estimation likely appear if endmembers are determined improperly. Increasing the spectra for endmembers is a practical and beneficial means for LSMM when there is not a priori knowledge, which emphasizes the necessity of building a comprehensive spectral library of urban materials. Furthermore, the LST retrieval from a single channel of Landsat 8 is more challenging as compared with the retrieval from the channels of its predecessors—Landsat 4/5/7.

1. Introduction

Land surface temperature (LST) recorded by remotely sensed observation is recognized as one of useful indicators of urban thermal environment (Jin, 2012; Voogt and Oke, 2003; Weng, 2009). Accurately quantitative description of urban thermal environment derived from LST is valuable, especially under the context of urbanization and global warming (Li and Elie, 2013; Grimm et al., 2008; Seto et al., 2014). Accurate land surface emissivity (LSE) is required for LST retrieval methods, especially for the widely used single channel methods (Duan et al., 2008; Jiménez-Muñoz and Sobrino, 2003; Jiménez-Muñoz et al., 2009; Qin et al., 2001; Zhang et al., 2006). It is recognized as a practicable way to obtain LSE from remotely sensed data through corresponding methods (Li et al., 2013a). Different approaches based on specific assumptions have been proposed for LSE estimation. These methods are generally categorized into three groups: (semi-) empirical methods, multichannel temperature emissivity separation methods, and physically based methods (Li et al., 2013a). For sensors (e.g. Landsat 4/5/7, CBERS02, and HJ1B) that have only one thermal channel, only the empirical methods are applicable in practice. The empirical methods are highlighted in Li et al. (2013a), owing to (a) their simplicity, (b) no requirement for accurate atmospheric correction, (c) relatively higher spatial resolution of the retrieved emissivity from multispectral reflectance, because multispectral reflectance (i.e. located in visible, near infrared, and the short-wave infrared regions) images have relatively higher spatial resolution compared to thermal infrared image(s), and (d) no requirement for information about the thermal channel(s). Generally, the empirical approaches include classification-based and spectral index-based methods. Land cover/use classified and representative emissivity

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values predefined are important for the classification-based method (Snyder et al., 1998; Peres and DaCamara, 2005; Sobrino et al., 2012). The spectral index-based method depends on the statistical relation between spectral indices and the emissivity of specific thermal channel. In practice, representative emissivity values are always assigned based on spectral library, which possibly ignore uncertainties in surface variations associated with seasonal and dynamical factors, such as phenology and soil moisture. Meanwhile, for the spectral index-based method, thresholds of spectral indices used for selecting pure endmembers or representatives are crucial. The spectral indices, such as the normalized difference vegetation index (NDVI) (Qin et al., 2004; Sobrino et al., 2008; Stathopoulou et al., 2007; Van de Griend and Owe, 1993; Valor and Caselles, 1996) and the normalized difference moisture index (NDMI) (Mallick et al., 2012), are calculated from the multispectral reflectance records in visible, near infrared, and short-wave infrared regions. Hybrid procedures combining both classification-based method and spectral index-based method have also been applied (Qin et al., 2004; Peres and DaCamara, 2005).

Accuracy of LSE is of utmost importance to the estimation of urban LST from remotely sensed imagery, because cities are heterogeneous (Sobrino et al., 2012). Limitations of the empirical methods for LSE may be more obvious when they are applied to urban areas. Additionally, mixed pixel in remotely sensed imagery is significant with medium spatial resolutions (e.g. the Landsat series, the CBERS series, and the HJ1B) (Chen et al., 2011; Weng, 2011). Sub-pixel estimation based on linear spectral mixture model (LSMM) is considered an improvement to traditional empirical methods (Peng et al., 2008; Mitraka et al., 2012). In spite of a large number of studies in which remotely sensed data were used to investigate urban thermal environment (Voogt and Oke, 2003; Weng, 2009; Tomlinson et al., 2011), only a few investigations address LSE related issues adequately to assess urban LST patterns (Qin et al., 2004; Wu and Li, 2006; Li et al., 2007; Stathopoulou et al., 2007; Sobrino et al., 2012; Mallick et al., 2012; Mitraka et al., 2012; Oltra-Carrió et al., 2012, 2014). In most investigations the importance and potential impacts of urban LSE have been ignored, often due to data unavailability.

It should be a critical question—whether urban LSE followed by LST retrieval can be accurately obtained through current methods. Potential challenges to urban LST retrieval are investigated in this paper, regarding the uncertainty in LSE estimation. The LST errors caused by LSE uncertainty are firstly deduced in Section 2. In Section 3, more insights into urban LSE are then obtained through three spectral libraries, with major considerations given to thermal channels of several specific sensors (Fig. 1). The performance and possible limitations of several widely used methods for urban LSE estimation are discussed in Section 4, and the challenges to urban LST retrieval through current single channel methods are presented accordingly.

2. Error model of land surface temperature

2.1. A theoretical error model

Assuming the surface as a Lambertian emitter–reflector, the radiative transfer equation (RTE) for a specific thermal band can be expressed in a simplified form, as follows:

$$L_{obs} = \left[\varepsilon_e B(T_s) + (1 - \varepsilon_e)L_{atm}^{\downarrow}\right]\tau + L_{atm}^{\uparrow} \quad (1)$$

where L_{obs} is the top-of-atmosphere (TOA) radiance detected by a space-borne sensor, τ is atmospheric transmissivity, $L_{atm}^{\uparrow}$ is the up-welling atmospheric radiance, and $L_{atm}^{\downarrow}$ is the down-welling atmospheric radiance. ε_e is land surface emissivity, T_s is land surface temperature, and $B(T_s)$ is the blackbody radiance given by the Planck's law. All variables in Eq. (1) are effective values, which are weighted averages according to the spectral response function (SRF) of the specific thermal channel.

The mixture of surface and atmospheric signals gives rise to difficulties in direct retrievals of LST and LSE from the TOA radiance, especially for the observation by a single thermal channel. Accurate LST retrieval from remotely sensed measurements requires both a proper characterization of atmospheric influence and an adequate knowledge of LSE (Peres and DaCamara, 2005). The impact of the LSE uncertainty on LST retrieval is exclusively discussed in this paper, from both theoretical and practical perspectives.

According to Eq. (1), the influence of LSE uncertainty on LST retrieval is modeled as Eq. (2).

$$\Delta T_s(\varepsilon_e) = \frac{\Delta\varepsilon_e}{\Delta\varepsilon_e + \varepsilon_e} \cdot \frac{\partial T_s}{\partial B(T_s)} \cdot \left[L_{atm}^{\downarrow} - B(T_s)\right] \quad (2)$$

where $\Delta\varepsilon_e$ is the error of LSE and $\Delta T_s(\varepsilon_e)$ is the corresponding LST error.

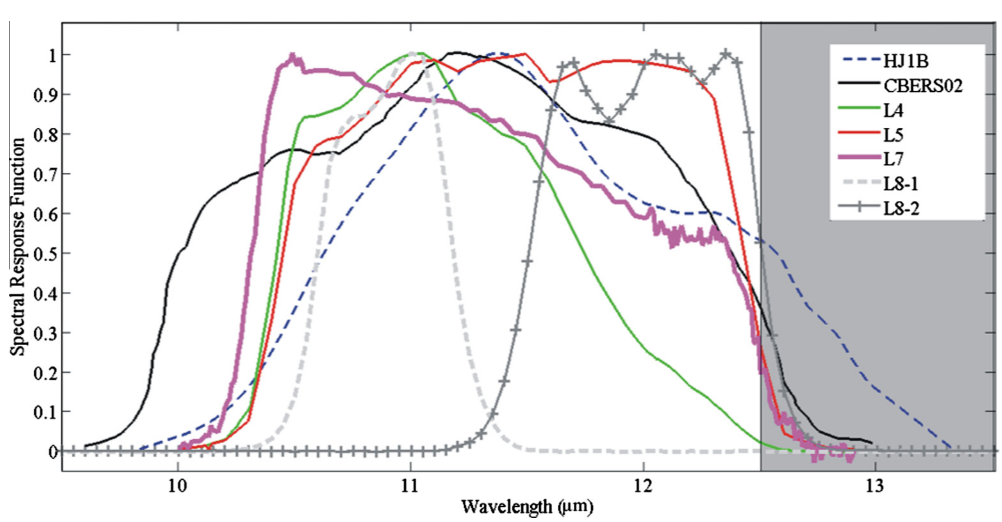

Fig. 1. Spectral response functions for the thermal channels of sensors on board different platforms. Effective wavelengths for these thermal channels are 11.576 μm (HJ1B), 11.237 μm (CBERS02), 11.154 μm (Landsat 4), 11.457 μm (Landsat 5), 11.269 μm (Landsat 7), 10.904 μm (Landsat 8-1), and 12.003 μm (Landsat 8-2), respectively, which are obtained through the "Trapezoid" strategy (Hu et al., 2011). The gray shaded area shows potential deficiencies of some spectra in the ASTER Spectral Library Version 2.0 as maximum wavelength does not exceed 12.5 μm.