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Estimating very high resolution urban surface temperature using a spectral unmixing and thermal mixing approach

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ABSTRACT

Land surface temperature (LST) plays a critical role in characterizing energy exchanges of the Earth's surface and atmosphere. Recent advances in thermal infrared (TIR) remote sensing technology enable the emergence of airborne very-high-resolution (VHR) TIR sensors to identify detailed LST distribution for environmental, geological and urban applications. However, the usage of airborne VHR TIR data may be limited by its high cost, long acquisition period, extensive data processing, etc. A cost-effective alternative could be VHR LST estimation. We proposed a physically based method, referred to as the VHR spectral unmixing and thermal mixing (VHR-SUTM) approach, to estimate LST at the meter level. Particularly, considering both spectral and thermal properties, spectral unmixing was employed to estimate fractional urban compositions for a comprehensive representation of heterogeneous urban surfaces. Further, VHR LST was modeled as a summation of the thermal features of representative urban compositions weighted by their respective abundances. Results suggest a high agreement between the resampled VHR LST estimates and the retrieved LSTs. With relatively high estimation accuracy (RMSE of 2.02 K and MAE of 1.51 K), the VHR-SUTM technique could serve as a promising and practical method for various applications in urban and environment studies.

1. Introduction

As an important environmental factor, land surface temperature (LST) plays a critical role in characterizing energy exchanges of the Earth's surface and atmosphere (Quattrochi and Luvall, 1999; Weng, 2009). A prominent example is the surface urban heat island (SUHI) phenomenon, which suggests that LST over an urban area is generally higher than that in its neighboring non-urbanized areas. With natural vegetated lands replaced by a wide range of anthropogenic materials during the process of urbanization, most physical properties of land surface, including albedo, heat capacity, conductivity, moisture, emissivity, etc., have been considerably modified, and accordingly resulted in decreased evapotranspiration (Shoshany et al., 1994; Friedl, 2002; Streutker, 2002; Chudnovsky et al., 2004). From a remote sensing perspective, such an urban–rural surface temperature variation can be detected using appropriate thermal sensors. Thermal infrared (TIR) remote sensing images, ranging from coarse resolution (e.g. Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS)) to medium resolution (e.g. Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+), and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)), have been widely employed for analyzing urban climate and environments (Streutker, 2003; Nichol, 1994, 2005; Lu and Weng, 2006; Weng, 2009). Moreover, the U.S. National Research Council (NRC) recently reported the Hyperspectral Infrared Imager (HyspIRI) decadal survey mission (NRC, 2007), according to which new spaceborne sensors with visible, near-infrared, shortwave infrared, and TIR wavebands will be launched. The potential TIR imagery of HyspIRI at a spatial resolution of 60 m may substantially improve the ability of thermal information measurement, primarily for the analyses of carbon cycle and ecosystems (Roberts et al., 2012).

In addition to coarse- and medium-resolution TIR imagery, recent advances in TIR technology enable the emergence of airborne very-high-resolution (VHR) thermal sensors to identify detailed LST distribution for a variety of applications, e.g. urban thermal pattern assessment, oil-spill detection, building heat loss mapping, urban energy efficiency monitoring and assessment, geologic mapping, anthropogenic material detection, etc. (Lo et al., 1997; Quattrochi et al., 1998, 2000; Gluch et al., 2006; Hay et al., 2011). In particular, Quattrochi and Ridd (1994, 1998) summarized three merits of VHR TIR imagery for urban thermal pattern analysis, including (1) convenient separation/identification of thermal behaviors of different urban surface materials, (2) spatial aggregation of segments with similarly thermal functions, and (3) inherent integration with various ecological models. In spite of these

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advantages, the applications of emerging airborne VHR TIR data are impeded by its limitations, including relatively high cost, long acquisition period, large masses of data, multiple pre-processing steps, etc. (Hay et al., 2011). Consequently, the estimation of VHR LST information could serve as a cost-effective alternative means. A straightforward method is to establish statistical associations between LST and parameters extracted from remote sensing imagery (Voogt and Oke, 2003; Weng, 2009). LST has been estimated through employing a great number of environmental and socio-economic factors, including geometry of street canyon, land use and land cover (LULC) type and change, normalized difference vegetation index (NDVI), green vegetation abundance, impervious surface abundance, landscape metrics, intensity of human activity, population density and distribution, etc. (Eliasson, 1996; Elvidge et al., 1997; Bottyán and Unger, 2003; Yuan and Bauer, 2007; Weng et al., 2011; Li et al., 2011). With current charge-coupled device (CCD) technology, however, only coarse-/medium-resolution TIR imagery can be acquired from spaceborne sensors. Due to the lacks of VHR TIR bands and/or synchronizing field measurements as the dependent variable in simple correlation/regression analysis against environmental indicators, it is impractical to establish such statistical relationships for VHR LST estimation.

One potential solution could resort to the physical mechanism underlying the SUHI phenomenon, particularly the interactions between land surface properties and thermal responses. In addition to the aforementioned statistical analysis, a few studies explored individual thermal responses of various urban land use/cover types using medium- to high-spatial resolution TIR imagery. For instance, Goward (1981) summarized three classes of urban land use types with significantly different thermal properties, i.e. natural areas, pavements, and buildings. Quattrochi and Ridd (1994, 1998) further expanded these three classes into seven more detailed land use types of urban thermal objects. Moreover, in conjunction with Ridd's vegetation–impervious surface–soil (V–I–S) model (Ridd, 1995), diverse diurnal thermal behaviors of a series of urban materials have been examined (Chudnovsky et al., 2004; Hartz et al., 2006; Gluch et al., 2006). Although different separation/classification schemes have been proposed to identify individual urban surface materials with "unique reactions of energy and moisture within an urban ecosystem" (Gluch et al., 2006), rare research has been conducted to model the composite thermal response from individual land covers. Therefore, the overall objective of this paper is to estimate high-resolution urban land surface temperature through incorporating thermal responses from representative urban materials with their respective fractional abundances. To reach this goal, we developed a two-step physically based method, referred to as the VHR spectral unmixing and thermal mixing (VHR-SUTM) approach. More specifically, two explicit objectives of this study are: (1) adopting spectral unmixing to derive fractional urban compositions, with a focus on their thermal responses, and (2) developing thermal mixing to estimate VHR LST through integrating the thermal responses of urban compositions and their respective abundances.

The remainder of this paper is structured as follows. Section 2 introduces study area and data. Section 3 presents the proposed VHR-SUTM method for LST modeling with IKONOS imagery. Modeling results and accuracy assessment are provided in Section 4. Finally, discussion and conclusions are given in Sections 5 and 6, respectively.

2. Study area and data

2.1. Study area

The study area includes the Town and Village of Grafton in Ozaukee County, Wisconsin, USA (see Fig. 1). The western side of the study area is the Town of Grafton, where major land use types include commercial, industrial, high- and medium-density residential, and civic (educational institutes, hospital, and government services) lands (Southeastern Wisconsin Regional Planning Commission (SEWRPC), 2000). The eastern side locates the Village of Grafton by the Lake Michigan, and its dominant land uses are low-density residential, agricultural, forest, wetlands, and other natural lands. The population of Grafton was 14,444 and the number of housing units was 5773 according to 2000 Census, with a growth rate of approximately 8% and 19% from 1990 respectively. Based on predictions from SEWRPC (2004a,b), such a trend of continuous development in Grafton is expected in the coming several decades. Due to the impact of urban LST on environmental health, internal microclimatology, human comfort and energy consumption, detailed urban thermal information may be of great help for planning practices, environmental monitoring and disease prevention and control in the study area. To construct the thermal mixing model, the retrieved LST of Cedarburg (see Fig. 1), an adjacent city of Grafton with almost identical climatic, environmental and socioeconomic status, was adopted to independently derive typical LST values of each land cover composition.

2.2. Dataset and LST retrieval

An IKONOS image acquired on September 3, 2002 with a resolution of 4 m was collected to derive subpixel land cover information. This image was rectified to a Universal Transverse Mercator (UTM) projection with WGS84 datum and UTM zone 16. At-satellite reflectance of this image was then derived from digital numbers (DNs), following the work of Taylor (2009). In addition, to obtain LSTs for model construction and validation, a Landsat TM TIR image acquired on September 6, 2002 was adopted at a resampled 30-m spatial resolution (U.S. Geological Survey, 2010). In addition, an aerial Digital Orthophoto Quarter Quadrangle (DOQQ) image acquired in 2002 was obtained for land cover fraction validation. The datum and projection of these images were set identically as those of the IKONOS image. Because of the cloud-free atmospheric condition and the small geographical extent of the study area, we did not carry out any atmospheric correction for both images. We also collected meteorological data from the University of Wisconsin-Milwaukee field station and the zenith wet delay estimate data (DeMets, 2012) for deriving LST information, respectively.

For LST retrieval from the Landsat TM TIR image, we employed the mono-window algorithm (MWA) proposed by Qin et al. (2001), which takes into account the effects of emissivity and atmosphere. Four important parameters of the MWA model, i.e. emissivity (ε_6), effective mean atmospheric temperature (T_a), brightness temperature (T_6) and atmospheric transmittance (τ_6), were predetermined respectively according to specific land surface properties and atmospheric condition of the study area (Qin et al., 2001; Okwen et al., 2011). First, ε_6 was determined using the NDVI thresholds method developed by Sobrino et al. (2001). Second, T_a was derived based on the acquisition date of the remote sensing image and the geographical location of our study area. Third, T_6 was derived following the work of Markham and Barker (1986) and Landsat 7 science data users handbook (Irish, 2000). Finally, we calculated τ_6 using the linear regression model with the empirical relationship between atmospheric transmittance and water vapor content according to the GPS meteorology method (Qin et al., 2001; Bevis et al., 1992, 1994; Rocken et al., 1995). These four resulting parameters were then input into the MWA model to retrieve LST information. More details of LST retrieval can be referred to Qin et al. (2001) and Okwen et al. (2011).