Remote Sensing of Environment 117 (2012) 125–134

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

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

Improving the estimation of urban surface emissivity based on sub-pixel classification of high resolution satellite imagery

Zina Mitraka [a,c,*], Nektarios Chrysoulakis [a], Yiannis Kamarianakis [b], Panagiotis Partsinevelos [c], Androniki Tsouchlaraki [c]

[a] Foundation for Research and Technology, Hellas, Institute of Applied and Computational Mathematics, N. Plastira 100, Vassilika Vouton, P.O. Box 1385, GR-71110, Heraklion, Greece
[b] School of Civil and Environmental Engineering, Cornell University, USA
[c] Technical University of Crete, Greece

ARTICLE INFO

Available online 8 September 2011

Keywords:
Land surface emissivity
Urban environment
Spectral mixture analysis
Constrained least absolute value algorithm

ABSTRACT

Information about the spatial distribution of urban surface emissivity is essential for surface temperature estimation. The latter is critical in many applications, such as estimation of surface sensible and latent heat fluxes, energy budget, urban canopy modeling, bio-climatic studies and urban planning. This study proposes a new method for improving the estimation of urban surface emissivity, which is primarily based on spectral mixture analysis. The urban surface is assumed to consist of three fundamental land cover components, namely vegetation, impervious and soil that refer to the urban environment. Due to the complexity of the urban environment, the impervious component is further divided into two land cover components: high-albedo and low-albedo impervious. Emissivity values are assigned to each component based on emissivity distributions derived from the ASTER Spectral Library Version 2.0. The fractional covers are estimated using a constrained least absolute values algorithm which is robust to outliers, and results are compared against the ones derived from a conventional constrained least squares algorithm. Following the proposed method, by combining the fraction of each cover component with a respective emissivity value, an overall emissivity for a given pixel is estimated. The methodology is applicable to visible and near infrared satellite imagery, therefore it could be used to derive emissivity maps from most multispectral satellite sensors. The proposed approach was applied to ASTER multispectral data for the city of Heraklion, Greece. Emissivity, as well as land surface temperature maps in the spectral region of 10.25–10.95 μm (ASTER band 13) were derived and evaluated against ASTER higher level products revealing comparable error estimations. An overall RMSE of 0.014776 (bias = −0.01239) was computed between the estimated emissivity obtained using the proposed methodology and the ASTER higher level product emissivity (AST05). The respective overall RMSE value for derived LST was found equal to 0.816935 K (bias = 0.67826 K).

1. Introduction

While cities cover only a small portion of the global land surface, most of the human population and related activities are concentrated in the urban environment, resulting in significant transformation of natural resources (Kennedy et al., 2011; Lambin et al., 2001). During the last decade, there has been a growing interest in studies concerning surface temperatures and urban energy budget characteristics. Such knowledge is significant to a range of topics in earth sciences, including urban climatology (Arnfield, 2003; Voogt & Oke, 2003), global environmental change, human–environment interactions, (Weng, 2009; Yang et al., 2003) and planning and management practices (Chrysoulakis et al., 2009). The energy budget of the urban surface is mainly defined by its albedo and Land Surface Temperature (LST), both of which can be derived from satellite observations (Chrysoulakis, 2003). To retrieve LST from satellite observations, three main effects have to be considered and corrected: angular, emissivity and atmospheric effects. Jiménez-Muñoz and Sobrino (2003) analyzed these effects and found that 1% uncertainty in emissivity can lead to an error on the LST up to 0.4 K.

Emissivity is a measure of the inherent efficiency of the surface to convert heat energy into radiant energy. Satellite-based emissivity estimates depend largely on the composition, roughness and other physical parameters of the surface, such as its moisture content (Becker & Li, 1990, 1995). By definition, the channel emissivity ε_i is given by Becker and Li (1990):

$$\varepsilon_i = \frac{\int f_i(\lambda)\varepsilon_\lambda B_\lambda(LST)d\lambda}{\int f_i(\lambda)B_\lambda(LST)d\lambda} \tag{1}$$

* Corresponding author at: Foundation for Research and Technology, Hellas, Institute of Applied and Computational Mathematics, N. Plastira 100, Vassilika Vouton, P.O. Box 1385, GR-71110, Heraklion, Greece. Tel.: +30 2810 391771, +30 6944240944 (Mobile); fax: +30 2810391761.
E-mail address: mitraka@iacm.forth.gr (Z. Mitraka).

0034-4257/$ – see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2011.06.025

where $B_\lambda(\mathrm{LST})$ is the Planck's function for black body emission, $f_i(\lambda)$ is the spectral response of the radiometer in channel i and ε_λ is the spectral emissivity. Although in Eq. (1), ε_i depends on LST, according to Becker and Li (1990), this variation of ε_i with LST is negligible ($\Delta\varepsilon_i = 10^{-4}$). Therefore, the channel emissivity can be expressed as:

$$\varepsilon_i = \frac{\int f_i(\lambda)\varepsilon_\lambda d\lambda}{\int f_i(\lambda)d\lambda} \tag{2}$$

The emissivity dependence on the physical condition of the surface imposes large temporal variations. This leads to a more complex undertaking of LST retrieval, often prone to largely varying and inconsistent accuracies. The emissivity of the surface affects the radiance measured from satellite sensors primarily in three significant ways (Prata, 1993): a) the reduction of emissivity from unity causes a reduction in the magnitude of the upwelling surface radiance; b) the nonblack behavior of the surface gives rise to a contribution from the reflected radiance from the surface; c) the anisotropy of the reflectivity and emissivity of the surface can substantially modify the total radiance received at the satellite. Other factors associated with surface emissivity effects are mixed pixel effects and zenith angle effects.

The main problem in determining emissivity from Eq. (2) is the observation of emissivity of natural surfaces at satellite spectral and spatial resolutions (Coll et al., 1994). The dimension of ground pixels in a satellite image is such that the characteristics of the surface may display substantial variation within a pixel. For instance, surface temperatures can vary by as much as 10 K over a few meters due to shadowing effects, variation in insolation and topographic effects (Prata, 1993). This strong horizontal heterogeneity introduces ambiguity to the definition of an overall emissivity and LST for a given pixel at a given scale. Furthermore ambiguity rises from emissivity, LST and their correlation measured at different scales, for instance, from different satellite sensors, or in-situ derived. This scale mismatch also makes validation against “ground truth” difficult.

By changing the viewing angle of the radiometer, the radiation mix from the same components is affected (Prata, 1994). Most natural surfaces show angular variation of emissivity higher or equal to 0.01, for viewing angles higher than 30° (Sobrino & Cuenca, 1999). These differences lead to absolute errors on LST equal to or higher than 0.4 K. As discussed by Sobrino et al. (1996), estimation of the angular variation of emissivity is a difficult problem, since there are only very few in-situ measurements of the angular variation of emissivity over land. Prata (1994) proposed a parameterization for the angular variation of emissivity for bare soil. For dry, bare surfaces, emissivity effects on LST are more important and need to be specified within an accuracy of ± 0.005. For vegetated surfaces, emissivity effects are minimized by cavity effects and angular effects are only important for structured vegetation (Sobrino et al., 1990). As explained by Prata (1994), cavity effects tend to increase the emissivity and reduce the spectral contrast.

Several methods have been developed to retrieve surface emissivity (Becker & Li, 1990; Kealy & Gabell, 1990; Snyder et al., 1998; Sobrino & Raissouni, 2000; Valor & Casseles, 1996; Watson, 1992). Dash et al. (2002) summarized different emissivity estimation techniques and analyzed their main constraints. Within a particular surface type, emissivity variation is not well known, but measurements suggest it is small, around ± 0.01, except when structural changes occur as in senescent vegetation. Thus, as explained by Prata (2002), the greatest concern for deriving LSTs is variation between (rather than within) surface types. The scheme for accounting for emissivity variations between surface types relies on a surrogate measure of surface structure. ASTER higher level emissivity and LST products are derived using the Temperature Emissivity Separation method (TES) (Gillespie et al., 1998). TES products have been validated and were found to perform within the specification of ± 0.015 for emissivity and ± 1.5 K for LST (Gillespie et al., 1998). Jiménez-Muñoz et al. (2006) developed an emissivity retrieval method for ASTER based on Normalized Vegetation Index (NDVI). Snyder et al. (1998) proposed a classification-based method to estimate emissivity from conventional static land cover classes and dynamic information, and developed an emissivity knowledge-base. Snyder et al. (1998) derived spectral coefficients from laboratory measurements of material samples (Salisbury et al., 1994; Salisbury & D'Aria, 1992, 1994; Snyder et al., 1997) with the use of linear Bidirectional Reflectance Distribution Function models and structural parameters from approximate descriptions of the cover type (Snyder & Wan, 1998). Uncertainties on estimated emissivity, when land-cover mapping methods are applied, are due to the limited number of land-cover types and the lack of updates in land-cover maps. LST errors increase almost linearly, and may reach 6 K in absolute magnitude for fairly small errors in emissivity (Yu et al., 2008).

Mapping the urban environment in terms of its physical components preserves the heterogeneity of urban land cover better than traditional land-use classification (Clapham, 2003; Ji & Jensen, 1999), characterizes urban land cover independent from analyst-imposed definitions (Jensen, 1983; Ridd, 1995), and captures accurately changes through time (Ji & Jensen, 1999; Rashed et al., 2005). The Vegetation-Impervious-Soil (VIS) model (Ridd, 1995) considers the combination of impervious surfaces, green vegetation, and exposed soil as the fundamental components of urban ecosystems if water surfaces are ignored. Lu and Weng (2004) refer to a number of studies where the VIS model is applied to characterize urban environments.

In this paper, a new methodology for estimating land surface emissivity from high resolution satellite imagery is proposed. The urban land cover is modeled using a variant of VIS model (Ridd, 1995) and the sub-pixel components of land cover are mapped using Spectral Mixture Analysis (SMA). Assuming that land surface emissivity can be expressed as a linear combination of the emissivities of all components inside a pixel, the spatial distribution of emissivity can be derived from visible and near infrared satellite observations.

2. Study area and datasets

The study area covers the broader area (approximately 360 km^2) of Heraklion, the larger city in the island of Crete, Greece (Fig. 1). Heraklion is one of the rapidly growing urban areas in Greece and exhibits a mixed land-use pattern that includes residential, commercial and industrial surfaces, transportation networks and rural surfaces. This area is suitable for analysis as it possesses a diversified urban and rural land cover.

An Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) image (Level 1B) acquired on July 10, 2006 (acquisition time approximately 09:10 UTC) under clear weather conditions, was used in this study (Fig.1). ASTER imagery contains four visible and near infrared (VNIR), five shortwave infrared (SWIR) and five thermal infrared (TIR) bands of spatial resolution 15 m × 15 m, 30 m × 30 m and 90 m × 90 m respectively. ASTER higher level products (for both land surface temperature and emissivity) were also available for the respective scene (LPDAAC, 2010). Therefore, the available surface emissivity and temperature maps were used to evaluate the performance of the proposed method and perform accuracy assessment.

A very high resolution orthophotomap derived from Ikonos satellite image acquired during the same period (Summer 2006) was also made available by Foundation for Research and Technology — Hellas (FORTH). This orthophotomap was used as an ancillary dataset for the selection of endmembers on ASTER multispectral imagery. Finally, MODIS derived precipitable water product was used to consider the atmospheric effects, while estimating LST as per Jiménez-Muñoz and Sobrino (2010).