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Study of the geometry effect on land surface temperature retrieval in urban environment

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ABSTRACT

This study presents a Single Channel Method using Urban Exitance Model (UEM-SCM) to retrieve land surface temperature (LST) from satellite data in an urbanized city, and evaluates the geometry effect on land surface temperature retrieval using single channel method and split-window algorithm. The UEM-SCM incorporates the effect of urban geometry and considers both reflection caused by the target pixel and its neighboring pixels. In order to evaluate the geometry effect, the retrieved LSTs with and without geometry effect were studied. Results show that the LSTs without geometry effect are generally higher than the LSTs with geometry effect. The temperature difference occurs because the material emissivity is always lower than the effective emissivity caused by multiple scattering and reflection in urban areas (cavity effect). The LST without geometry effect also cannot fully capture the variability and complexity of urban thermal patterns. The temperature difference between with and without the geometry effect can reach 2 K in built-up areas. A comparison was also conducted between LST retrieved by split-window algorithm with and without geometry effect. Results show that the LST retrieved by split-window algorithm without geometry effect has generally higher values than the one with the geometry effect, e.g. 1.1 K on average and 1.5–2 K in built-up areas. The geometry effect will be removed and mis-deemed as atmospheric effect when the split-window algorithm without geometry effect is applied in urban areas. The split-window algorithm with the geometry effect can be used to distinguish between geometry and atmospheric effect in further study.

1. Introduction

With the rapid urbanization in the world, Urban Heat Island (UHI) is now one of the major problems posed to human beings and it is not only directly responsible for adverse health effect from exposure to extreme thermal conditions, but also has indirect effect on human health via air pollution (Frumkin, 2002; Rizwan et al., 2008; Tan et al., 2010). Urban heat island is known as the higher temperature observed in urban areas than its surroundings (Oke, 1982; Rizwan et al., 2008). UHIs have long been studied by ground-based observation of air temperature (Voogt and Oke, 2003). However, the spatial patterns in the temperature difference cannot be easily depicted by air temperature measurements at discrete locations, thus synoptic observations of Land Surface Temperature (LST) using satellites provide an alternative for assessing and understanding the Surface Urban Heat Island (SUHI) effect. The land surface temperature obtained by remotely sensed data is a new viewpoint to understand UHI and define the SUHI (Voogt and Oke, 2003; Hu and Brunsell, 2013). LST is not only one of the important parameters in the physical processes of surface energy and water balance at local, regional and global scales (Li et al., 2013), it is also an important parameter for urban climatic studies (Voogt and Oke, 2003; Pu et al., 2006). Several methods have been built for retrieving LST from remote sensing data (Li et al., 2013), however, most of these methods are based on the assumption that the surface is smooth, homogeneous, and isothermal (Gillespie et al., 1998; Sobrino et al., 2004). The urban temperature anisotropy is caused by the complex urban geometric characteristics and different components of mixed pixels. The surface temperature anisotropy caused by different components of mixed pixels was analyzed (Menenti et al., 2001; François, 2002; Jia et al., 2003; Zhan et al., 2013) and the methods for separating the component temperatures through directional thermal infrared data in rural areas were also studied (Menenti et al., 2001;

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François, 2002; Jia et al., 2003). These studies assumed the components in mixed pixels to be homogenous and uniform, however, and this assumption can only be valid for rural areas with vegetation and soil covers. Considering the complicated urban geometry and material characteristics in urban areas, specific methods should be studied. The directional anisotropy of surface temperature caused by different geometries in urban areas was analyzed (Voogt and Oke, 1998; Lagouarde et al., 2004, 2010, 2012; Lagouarde and Irvine, 2008) and these studies showed that the effective anisotropy should be considered in the surface temperature retrieval over urban areas. Lagouarde et al. (2004) analyzed the angular variation of surface temperatures caused by the complex canopy structure and results showed that the variation in surface temperature ranges between −5 and +7 K. Lagouarde et al. (2010, 2012) analyzed the anisotropy of surface temperature over urban areas during day- and night-time, and results showed that the structure of urban canopy contributed to the anisotropy of surface temperature significantly. Voogt and Oke (1997) compared complete surface temperature (taking into account the total active surface areas) and remote sensing surface temperature, and results showed that using remotely observed surface temperatures without the geometry effect over urban areas has significant biases. It is because all remote sensing measurements of surface temperature show an incomplete estimate of the total urban surface temperature, and a mixed target exitance should be considered which includes the multiple reflection and scattering by urban canopy.

With the development of remote sensing technology, many studies have been conducted using satellite imagery to retrieve land surface temperature (Chen et al., 2006; Yuan and Bauer, 2007; Li et al., 2011). These methods assume that (i) the surface is homogeneous, and (ii) radiances are directly corrected with emissivity values of materials and derived to land surface temperature, however these emissivities are traditionally based on land cover classification data which have not considered the multiple scattering and reflection caused by urban geometry. Due to the multiple scattering and reflection, the radiance leaving the ground surface is different from the emittance by a pixel, since the radiance leaving from ground surface involves both the scattered and reflected radiance within the pixel and from adjacent pixels. Thus the term exitance is more appropriate to refer to the radiance leaving the surface. The geometry effect on the effective emissivity has been discussed in several studies (Sutherland and Bartholic, 1977; Arnfield, 1982; Harman et al., 2004; Danilina et al., 2012; Yang et al., 2015). Sutherland and Bartholic (1977) analyzed the cavity effect on the canopy of row crops and results showed that the effective emissivity was related with the geometry of canopy of row crops. Harman et al. (2004) analyzed the relationship between building geometry and radiation using a micro-climate urban model. Results showed that the effect of multiple reflection caused by geometry was significantly different when different material emissivities were assumed. Danilina et al. (2012) built and used a radiosity model to predict effective emissivity and spectral radiometric temperatures for rough surface. However, such a model is time- and computationally-demanding. The urban effective emissivity using a parameterization based on the Sky View Factor (SVF) has recently been developed and an exitance model for urban areas has also been built (Yang et al., 2015). Yang et al. (2015) investigated the effect of geometry on the effective emissivity in urban areas, and results show that the geometry has significant cavity effect in urban areas, when material emissivity is low, the cavity effect is more significant. In order to evaluate the impact on land surface temperature retrievals of urban geometry, single channel method and split-window algorithms were used to retrieve the LST based on different emissivities, which are the material emissivity with and without the geometry effect in this study.

2. Data

United States Geological Survey (USGS) states that due to the large calibration uncertainty associated with band 11 of Landsat 8 image, it is recommended that users refrain from only relying on band 11 data in quantitative analysis of the TIRS data (https://landsat.usgs.gov/calibration_notices.php). However, results from the evaluation of radiometric performance of the Thermal Infrared Sensor onboard Landsat 8 showed that the effect of NEΔT on LST retrieval with the newly-developed split-window algorithm contributed only 3.5% to the LST error (Ren et al., 2014). Thus, the thermal images of band 10 and band 11 of Landsat 8 observed on December 31st, 2013 were used in this study, but only band 10 was used to retrieve urban surface temperature based on single channel method, while both band 10 and band 11 were used to retrieve the urban surface temperature with the split-window algorithm. Airborne Lidar data with high spatial resolution (1 m) (Lai et al., 2012) and the building GIS data from Hong Kong Civil Engineering and Development Department and Hong Kong Lands Department have been used to calculate the Sky View Factor of Hong Kong (Yang et al., 2015). The land use classification data from the Hong Kong Planning Department and building GIS data were used to obtain the material emissivity of Hong Kong (Fig. 1). The land use classification data provide land use information, e.g. tree, grassland and impervious surface with spatial resolution of 6 m. Building GIS data were used to distinguish the impervious surface in buildings and road pavements. The material of buildings was assumed as general construction materials, e.g. cement, concrete and bricks. Roads were assumed to be constructed from asphalt, cement or concrete. Since it was not possible to obtain the exact material of each land cover, the average material emissivity spectra derived from library were then used to estimate the material emissivity for buildings and roads. The spectral Library of Impervious Urban Materials (Kotthaus et al., 2014) was adopted in this study. Considering Hong Kong is sub-tropical climate and most of the trees are evergreen, material emissivity of evergreen trees from ASTER Spectral Library 2.0 (Baldridge et al., 2009) was used, and the emissivity of evergreen trees is deemed as the emissivity of the vegetation canopy (Baldridge et al., 2009). The material emissivity of green grass from ASTER Spectral Library 2.0 (Baldridge et al., 2009) was taken as the material emissivity of the class of grassland. The urban areas of Kowloon Peninsula and part of Hong Kong Island were selected in this study. Both rural mountainous and water areas were masked and excluded from further study. The atmospheric water content was acquired from the AERONET 2.0 level product (Holben et al., 2006) from the AERONET station in the Hong Kong Polytechnic University, and the observation time was December 31st, 2013, 2:48:18 (UTC), which was the closest to the satellite overpass time (December 31st, 2013, 2:53:31 (UTC)). The total atmospheric water content was 1.09 g/cm^2. The sea surface temperatures near the weather station of Hong Kong International Airport at 3:00:00 (UTC), December 31st, 2013 were obtained from the Hong Kong Observatory to evaluate the atmospheric correction of the single channel method and split-window algorithm.

3. Method

In this study, the geometry effect on urban surface temperature retrieval was evaluated, by comparing the surface temperatures retrieved without the geometry effect and those with geometry effect parameterized using Sky View Factor. First, the Landsat 8 band 10 TIR image was used to retrieve (i) land surface temperature based on the Single Channel Method using the Urban Exitance Model (UEM-SCM), i.e. with geometry effect, and (ii) the ordinary