https://doi.org/10.1016/j.isprsjprs.2016.09.007

Development of an Improved Urban Emissivity model based on Sky View Factor for retrieving effective emissivity and surface temperature over urban areas

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Abstract

This study aims to evaluate the effects of urban geometry on retrieval of emissivity and surface temperature in urban areas. An improved urban emissivity model based on sky view factor (IUEM-SVF) was further enhanced to consider all radiance contributions leaving the urban canopy, including (i) emission by all facets within an instantaneous field of view (IFOV); (ii) reflection by all facets of emission from surrounding facets; and (iii) propagation of emitted and reflected radiation with multiple reflections (scattering) within a complex 3D array of urban objects. The effective emissivity derived from IUEM-SVF was evaluated with a microscale radiative transfer and energy balance model: Temperatures of Urban Facets in 3-D (TUF-3D). IUEM-SVF performs well when urban facets have uniform emissivity and temperature; e.g., root mean square deviations (RMSD) are less than 0.005 when material emissivity is larger than 0.80 ($\varepsilon \geq 0.80$). However, when material emissivities are variable within the observed target, differences of effective emissivity between IUEM-SVF and TUF-3D become larger, e.g., RMSD of 0.010. When the effect of geometry is not considered and a mixed pixel emissivity is defined, the difference is even much larger (i.e. 0.02) and this difference increases with the decrease of sky view factor. Thus, the geometry effect must be considered in the determination of effective emissivity. Effective emissivity derived from IUEM-SVF is used to retrieve urban surface temperature from a nighttime ASTER thermal infrared image. Promising results are achieved in comparison with standard LST products retrieved with the Temperature and Emissivity Separation (TES) algorithm. IUEM-SVF shows promise as a means to improve the

accuracy of urban surface temperature retrieval. The effect of thermal heterogeneity on the effective emissivity was also evaluated by TUF-3D, and results show that the thermal heterogeneity cannot be neglected since the RMSD between the effective emissivity based on TUF-3D and IUEM-SVF is relatively large.

Keywords: emissivity; temperature, geometry; thermal image

1. Introduction

Land Surface Temperature (LST) obtained by remotely sensed data provides a synoptic view and an effective measure of the Surface Urban Heat Island (SUHI), by observing the temperature differences between urban surfaces and rural areas (Dousset and Gourmelon, 2003; Voogt and Oke, 2003; Hu and Brunsell, 2013). For a flat and homogenous surface, remote sensors obtain surface exitance and emittance, after correction for atmospheric effects and taking into account the reflection of atmospheric emission. Surface temperature can be retrieved from the material emissivity and surface emittance through the Planck function (Sobrino et al., 2004; Sobrino et al., 2012). However, the geometry of urban areas is always complex. This results in anisotropy of satellite-observed surface emittance, due to the complexity of urban geometry and the different component temperatures within mixed pixels. The effect of different component temperatures in a mixed pixel over rural areas has been well-studied (Sobrino and Caselles, 1990; Menenti et al., 2001; Jia et al., 2003; Chen et al., 2004; Rasmussen et al., 2011; Ren et al., 2011; Guillevic et al., 2013;Ren et al., 2014; Cao et al., 2015). Other studies of directional anisotropy of surface temperature have shown that geometric effects should be considered in the retrieval of surface temperature over urban areas (Voogt and Oke, 1998; Lagouarde et al., 2004; Soux et al., 2004; Lagouarde and Irvine, 2008; Voogt, 2008; Lagouarde et al., 2010; Lagouarde et al., 2012; Duffour et al., 2016; Krayenhoff and Voogt, 2016). The aforementioned studies have examined different component effects on the radiance measured within the IFOV, but have not studied the impacts of the complex building geometry and thermal heterogeneity on the retrieval of effective emissivity and land surface temperature in urban environments.

A few terms of thermal infrared radiometry are first defined in this study: (i) emittance, (ii) exitance, and (iii) effective emissivity (Becker and Li, 1995; Norman and Becker, 1995; Norman et al., 1995). The emittance is the radiance emitted by all horizontal surfaces and vertical facets directly. The exitance is the sum of the emittance, the radiance re-emitted after absorption and radiance reflected by the surfaces and building facets. The effective emissivity is defined as the ratio of the total exitance of a pixel to the emittance of a blackbody at the same temperature (Yang et al., 2015a). Due to the multiple scattering and reflection caused by buildings in urban environments, the exitance in built-up areas is different from surface emittance. Multiple scattering and reflection also increase the radiance absorbed and emitted by the 3D-surface within a satellite pixel (Yang et al., 2015a). The total exitance of built-up areas is thus higher than that of a flat surface with the same material and temperature. The term “exitance” is thus more appropriate than emittance and it refers to the radiance leaving the urban canopy. For satellite data with a constant IFOV or footprint, the thermal sensor measures the exitance and not only the emittance. Thus, it is not always accurate to use a material emissivity to retrieve the surface temperature directly from the exitance, and an effective emissivity should be derived. If the surface is flat, the exitance is similar to the surface emittance, which can be derived from material emissivity and the Planck function, with a small contribution owing to reflection of atmospheric emittance. The exitance at the top of the urban canopy includes both the radiance emitted and that reflected by each facet (e.g. horizontal and vertical) of the 3D environment. Thus, the exitance can be determined by the three dimensional urban geometry, component temperature and material emissivity of surface components. The relationship between effective emissivity and geometry effect has been discussed in several studies (Sutherland and Bartholic, 1977; Harman et al., 2004; Danilina et al., 2012; Yang et al., 2015a).

In order to improve the accuracy of retrieval of urban surface temperature from the average exitance measured by space- or airborne-sensors over a footprint (i.e., from the IFOV), Yang et al (2015a) parameterized the urban effective emissivity using the sky view factor (UEM-SVF). This model considers the additional radiance caused by the cavity effect and the scattered radiance from neighboring pixels and the atmosphere, however it does not include radiance scattered by the surface elements within the pixel directly reflected to the sky. In this study, the UEM-SVF method was further improved by considering all radiance contributions leaving the urban canopy: (a) emission by all facets within an IFOV; (b) reflection by all facets of radiation emitted by the surroundings; (c) propagation of emitted and reflected radiation with multiple reflections (scattering) within the complex 3D array of urban objects. Thus the improved UEM-SVF, hereafter "IUEM-SVF", was to calculate the cavity effect on emission and reflection separately, while the UEM-SVF in Yang et al. (2015) only accounts for the cavity effect on emission. In addition, the IUEM-SVF was evaluated with a micro-scale three-dimensional (3D) radiation exchange and urban energy balance model, Temperatures of Urban Facets in 3D (TUF-3D) (Krayenhoff and Voogt, 2007). TUF-3D model can be applied to calculate an effective emissivity, which takes all radiative interactions within a scene into account during calculation at a sub-facet resolution specified by the user (Krayenhoff and Voogt, 2007). Subsequently, TUF-3D was used to evaluate the effect of thermal heterogeneity on urban effective emissivity and surface temperature retrieval.

Additionally, the IUEM-SVF was used to retrieve urban surface radiometric temperatures from the ASTER Band 13 data on December 16th, 2015. These temperatures were subsequently compared with the surface temperature product ASTER 2B03 derived from Temperature and Emissivity Separation (TES) algorithm (Gillespie et al., 1998). The ASTER TES algorithm is based on an empirical relationship between the minimum spectral emissivity ($\varepsilon_{\min}$) and Minimum-Maximum Difference (*MMD*), established by analyzing 86 laboratory TIR emissivity spectra data (Gillespie et al., 1998). Oltra et al. (2014) analyzed the performance of the ASTER TES algorithm based on simulated data and the $\varepsilon_{\min}$-*MMD* relationship derived from material emissivity over urban areas and results showed that the retrieved emissivity was higher than the material emissivity (Oltra et al., 2014). This is because the radiance obtained by remote sensors is affected by multiple reflections caused by geometry effect over urban areas and the actual spectral radiance observed over urban areas does not follow the empirical relationship $\varepsilon_{\mathrm{min}}$-*MMD*. The limitation of the application of TES in urban surface temperature was also analyzed in this study.

2. Data

Kowloon Peninsula of Hong Kong was selected as the study area for this research (Figure 1). One set of airborne high resolution thermal images acquired at 12:57 (Hong Kong noon time) on August 6th, 2013 was used to estimate differences in component temperatures. The component temperatures were derived by sampling the image data. The material of buildings was taken as concrete and cement. The mean rooftop temperature (Tr) is 328.56 K, the mean street temperature (Ts) is 316.64 K, and mean wall temperature (Tw) is 304.94 K, respectively, in a built-up area of Kowloon peninsula, at 22.85 ^{o}N, 114.08 ^{o}E.

The ASTER thermal radiance data on December 16th, 2015 14:36 (UTC) (Hong Kong local time is 10:36 pm) were used to retrieve urban surface temperature using the single channel method since the urban radiative transfer model can be applied in urban surface temperature retrieval using single channel method, while the ASTER 2B01 LST product was used to evaluate the derived LST from our improved effective emissivity model and single channel method. ASTER Band 13 was selected for LST retrieval since band 10 and 14 which are close to the edge of atmospheric window, are more easily affected by atmospheric effects. In addition, a declining of sensitivity of band 12 has also been reported (Nichol et al., 2009).

High spatial resolution airborne Lidar data (Lai et al., 2012) and building GIS data covering the entire Hong Kong territories were acquired for calculating SVF. The LiDAR data and 3D building data are provided by the Hong Kong Lands Department and the Hong Kong Civil Engineering and Development Department. The method of calculating SVF on vertical facets is based on the method presented by Kanda et al. (2005), Zakšek et al. (2011) and Yang et al. (2015). Land use and land cover data e.g. woodland, grassland and impervious surface with 6 m resolution were also used. Land use and land cover data are provided by the Hong Kong Planning Department. The building GIS data were used to distinguish the impervious surface on buildings and road pavements. More details about the land use and land cover data, building GIS data, as well as the airborne Lidar data can be found in Yang et al. (2015b). The spectral Library of Impervious Urban Materials (Kotthaus et al., 2014) and spectral response function of ASTER band 13 were used to derive the emissivities of building and impervious surface, where ASTER Spectral Library 2.0 (Baldridge et al., 2009) and spectral response function of ASTER band 13 were used to derive the emissivities of trees and grass. The spectral emissivity of wall facets, rooftop, road pavement, tree, and grass were 0.886, 0.945, 0.948, 0.973, and 0.986 respectively in ASTER band 13. More information on the spectral emissivity of ASTER band 13 can be found in Yang et al. (2015a).

"Insert Figure 1 here"

3. Method

3.1 IUEM-SVF model

Assuming the radiometric data are acquired by a satellite sensor at relatively low spatial resolution and at only one view angle, the component temperatures within a pixel cannot be easily observed. The IUEM-SVF model assumes that the pixel is isothermal, thus the effect of thermal heterogeneity on radiative transfer in mixed pixels is not accounted for. If the geometric effect is considered and the thermal heterogeneity effect is not accounted for, the exitance of pixel i with the cavity effect on emission can be defined as $\varepsilon(\mathrm{i})' B\left(T_s(i)\right)$ and $\varepsilon(\mathrm{i})'$ can be formulated as (Yang et al., 2015a):

$$\varepsilon(\mathrm{i})' = \varepsilon(\mathrm{i}) / [1 - (1 - \varepsilon(\mathrm{i}))(1 - v_{sky}(i))] \quad (1)$$

where $T_s(i)$ is the surface radiometric temperature of pixel i for the isothermal pixel, B is the Planck function. $\varepsilon(\mathrm{i})'$ is the effective emissivity due to the cavity effect within the pixel i. $\varepsilon(\mathrm{i})$ is the material emissivity of the pixel i and can be calculated as the area-weighted average of the components in a mixed pixel using very high resolution land use data and building GIS data. $v_{sky}(i)$ is the Sky View Factor (SVF) of pixel i. This equation accounts for the increases in emission due to the cavity effect in pixel i. The SVF is defined as the fraction of the hemisphere occupied by the sky observed at a certain location (Zakšek et al., 2011). The SVF was determined from a Digital Surface Model (DSM) along with a search radius, and SVF values determined in different search directions were averaged over a single pixel.

The exitance is the fraction of these radiation components (a, b, c in Equation 2) reflected to the sky: (a) radiance emitted within the pixel but blocked by wall facets of buildings within a pixel; (b) radiance from sky; (c) radiance from adjacent pixels. $v_{sky}(i)\big(1-\varepsilon(\mathrm{i})\big)$ is the fraction of all radiance reflected to sky. Then the mean radiance, $Ref_1(i)$, received by pixel i and then reflected to sky after the first reflection, can be calculated as:

$$Ref_1(i) = v_{sky}(i)\big(1-\varepsilon(\mathrm{i})\big)\{\underbrace{\Big(1-v_{sky}(i)\Big)\varepsilon(\mathrm{i})B\big(T_s(i)\big)}_{(a)} + \underbrace{v_{sky}(i) * R_{at}^{\downarrow}(i)}_{(b)} + \underbrace{v_{adj}(i) * R_{adj}}_{(c)}\} \qquad (2)$$

$R_{at}^{\downarrow}(i)$ is the atmospheric downward radiation (assumed isotropic), R_{adj} is the mean radiance of the adjacent pixels. $v_{adj}(i)$ is the view factor from the pixels surrounding pixel i (Yang et al., 2015b).

After a second reflection within the pixel *i*, the radiance reflected to sky can be written as:

$$Ref_2(i) = v_{sky}(i)\big(1-\varepsilon(\mathrm{i})\big)\Big(1-v_{sky}(i)\Big)\big(1-\varepsilon(\mathrm{i})\big) * \{(1-v_{sky}(i))\varepsilon(\mathrm{i})B\big(T_s(i)\big) + v_{sky}(i) * R_{at}^{\downarrow}(i) + v_{adj}(i) * R_{adj}\} = \big(1-\varepsilon(\mathrm{i})\big)(1-v_{sky}(i))Ref_1(i) \qquad (3)$$

After n^{th} reflection within the pixel *i*, the radiance reflected to sky can be formulated as:

$$Ref_n(i) = (1 - v_{sky}(i))(1 - \varepsilon(i))Ref_{n-1}(i) \tag{4}$$

Then the total reflected radiance can be written as:

$$\mathrm{Ref}(i) = Ref_1(i) + a * Ref_1(i) + \cdots + a^{n-1} * Ref_1(i) = \frac{Ref_1(i)\{1 - a^{m-1}\}}{1-a} \tag{5}$$

where $a = (1 - v_{sky}(i))(1 - \varepsilon(i))$

When m tends to infinity, a^{m-1} tends to 0, thus $\mathrm{Ref}(i)$ can be rewritten as:

$$\mathrm{Ref}(i) = \frac{Ref_1(i)}{1-a} \tag{6}$$

And combining equation 2 with equation 6, the equation is:

$$\mathrm{Ref}(i) = \frac{v_{sky}(i)(1-\varepsilon(\mathrm{i}))}{1-a}\{(1 - v_{sky}(i))\varepsilon(i)B(T_s(i)) + v_{sky}(i) * R_{at}^{\downarrow}(i) + v_{adj}(i) * R_{adj}\} \tag{7}$$

where $v_{sky}(i)(1 - \varepsilon(\mathrm{i}))/(1 - a)$ on the right side of Equation 7 is equal to $(1 - \varepsilon(\mathrm{i})')$. Then the total exitance on the urban canopy can be defined as:

$$\mathrm{E}(i) = \varepsilon(\mathrm{i})' B\big(T_s(i)\big) + \mathrm{Ref}(i) = \varepsilon(i)' B\big(T_s(i)\big) + (1 - \varepsilon(i)')\{(1 - v_{sky}(i))\varepsilon(i) B\big(T_s(i)\big) + v_{sky}(i) * R_{at}^{\downarrow}(i) + v_{adj}(i) * R_{adj} \quad (8)$$

This is the exitance, i.e. the radiance leaving the urban canopy, which is observed by remote sensors. $(1 - \varepsilon(i)')\{(1 - v_{sky}(i))\varepsilon(i) B\big(T_s(i)\big) + v_{sky}(i) * R_{at}^{\downarrow}(i) + v_{adj}(i) * R_{adj}\}$ in Equation (8) is the fraction of atmospheric emittance and radiance, reflected by adjacent pixel and the sub-surface within the pixel i. $\varepsilon(\mathrm{i})'$ is the effective emissivity of the surface within a pixel and $(1 - \varepsilon(\mathrm{i})')$ is the effective reflectance of the pixel when the transmittance is 0.

In order to estimate $\varepsilon(\mathrm{i})'$ using TUF-3D, the atmopheric emittance was defined as 0 and the adjacent pixel effect was also neglected. This allows the ratio of the total exitance to the radiance of the blackbody at the same temperature to be written as:

$$\varepsilon(i)'' = \varepsilon(i)' + (1 - \varepsilon(i)')(1 - v_{sky}(i))\varepsilon(i) \quad (9)$$

The first term in Equation (9), $\varepsilon(i)'$, is effective emissivity of the pixel i, which considers the additional emitted radiance because of the re-absorption caused by blockage of sub-surface within pixel i (Yang et al., 2015a). The term $(1 - v_{sky}(i))\varepsilon(i)$ is the fraction of blocked radiance by the urban structures within pixel i and $(1 - \varepsilon(i)')$ is the effective reflectance of pixel i to the sky, thus the term in Equation (9), $(1 - \varepsilon(i)')(1 - v_{sky}(i))\varepsilon(i)$, is the fraction of the radiance emitted by facets within pixel i onto other facets within pixel i and from there reflected back to the sky. This is the IUEM-SVF model of urban effective emissivity under the condition that the atmospheric downward radiance and adjacent pixel effect are removed from the total exitance. When SVF tends to 0 under the theoretical condition, the reflection tends to 0 and all radiances are absorbed, i.e. $\varepsilon(i)'$ tends to 1, similar to an “effective” blackbody. When the SVF tends to 1, the surface emits to the sky and no radiance is intercepted and re-absorbed, thus $\varepsilon(i)'$ is the material emissivity and the reflection among facets within a pixel tends to 0. If material emissivity of sub-surface within the pixel is the same, effective emissivity increases with decreasing SVF. For the real urban areas of Hong Kong, the values of SVF between 0.22 and 0.91 located between the 2.5% and 97.5 % under the normal distribution curve.

3.2 TUF-3D model

The TUF-3D model (Krayenhoff and Voogt, 2007) was used to evaluate the results from the IUEM-SVF model and to analyze the relationship between exitance and surface temperature. The radiation model of the TUF-3D uses the radiosity approach with analytical view factors and accounts for all (effectively infinite) radiation reflections in a scene (Krayenhoff and Voogt, 2007). TUF-3D calculates the upward radiation (radiation to sky in the scene) and the radiation balance of each facet (e.g. radiation balances of wall, street and rooftop) considering the effect of geometry. More detail about TUF-3D can be found in Krayenhoff and Voogt (2007).

3.3 Comparison between IUEM-SVF and TUF-3D

The TUF-3D model is based on the Stefan-Boltzmann law and broadband emissivity. However, remote sensing applications require narrowband spectral emissivity to retrieve the land surface temperature and the geometry effect should be considered. The radiative transfers of narrowband and broadband longwave radiation in urban areas are the same, thus the impact of urban geometry on effective emissivity can be evaluated using TUF-3D by specifying the narrowband material emissivities as the inputs. Additionally, the optimized version of TUF-3D used here only represents relatively simple urban covers with urban geometry characterized by a constant ratio of building height to building spacing. For each experiment, the ratio of building height to spacing was varied between 0.5 and 4, at an interval of 0.5, i.e. eight urban geometry cases were considered. The SVF values ranged from 0.59 to 0.86 across the cases.

Experiments to evaluate IUEM-SVF effective emissivity with TUF-3D are designed as follows and the summary of the settings for TUF-3D can be refereed Table 1:

a) In order to evaluate the geometry effect with material homogeneity and isothermal sub-surfaces, uniform surface temperature and material emissivities for all facets are defined in TUF-3D. The surface temperature was set as 303.15 K. Four values of emissivity were used, e.g. 0.8, 0.85, 0.90, 0.95 for uniform material emissivity for each numerical experiments (Case a1, a2, a3 and a4 in Table 1). Geometry is the only variable parameter.

b) Effective emissivity is usually calculated as the area-weighted average of the component emissivity without considering the effect of geometry or spatial thermal heterogeneity in the application over urban areas (Case b in Table 1). These estimates were then evaluated with TUF-3D, assuming the same temperature for all components.

c) The IUEM-SVF, which accounts for geometry and the area-weighted average of component emissivities, was used to estimate the effective emissivity in surface temperature retrieval from satellite remote sensing data. The configuration applied in TUF-3D is different to previous approaches, i.e. the material emissivity is specified for each facet, but all facets are assumed to have the same temperature to evaluate the effect of the material heterogeneity (Case c). The comparison between IUEM-SVF and TUF-3D was designed to evaluate whether it is necessary to consider the actual 3D distribution of surface emissivity. IUEM-SVF does not account for thermal heterogeneity of mixed pixels. The area-weighted average of the component emissivities in a mixed pixel was applied. The SVF is applied to account for the effects of geometry. The differences in effective emissivity between IUEM-SVF and TUF-3D are, therefore, related to the 3D distribution of emissivity of facets.

d) In some cases, urban spaces are highly complex in terms of both geometry and heterogeneity of emissivity. Under these conditions, the spatial heterogeneity of surface temperature may become large. This aspect cannot be evaluated using IUEM-SVF, however TUF-3D can be used. To determine realistic within-pixel thermal heterogeneity, airborne thermal image data at very high spatial resolution is used. Component temperatures based on the airborne images were input into TUF-3D to analyze the effect of thermal heterogeneity on radiative transfer in urban spaces (Case d1 and d2 in Table 1). The effective emissivity based on TUF-3D and effective emissivity based on IUEM-SVF under the isothermal cases c) was compared to evaluate the thermal heterogeneity effect on the effective emissivity and surface temperature retrieval.

TUF-3D calculates upwelling radiance at the top of the urban canopy and the full radiative balance of each facet (and sub-facet components). Since emittance, reflectance and exitance are calculated separately, the effects of the geometry of built-up space can be evaluated in detail. TUF-3D calculates the radiation flux density reaching a horizontal plane in the sky, i.e. it is the signal captured by a nadir-oriented radiometer with ~180° field of view. The radiation flux density calculated using TUF-3D, accounts for the actual 3D distribution of material emissivity and thermal heterogeneity in case d1 and d2, respectively.

To evaluate the impact of using a nadir – viewing imaging radiometer to retrieve the radiometric surface temperature of a complex 3D urban surface, two effective emissivities were defined and calculated. A first effective emissivity was obtained by combining the upwelling radiation calculated by TUF-3D (and measured by a nadir – viewing imaging radiometer) with the complete surface temperature, i.e. the area-weighted average of all facet temperatures. Then a second effective emissivity (mean effective emissivity of the 3D surface) was calculated by taking the mean exitance over all facets, i.e. including the vertical walls not observable by a narrow field of view nadir-oriented radiometer. To compute this second effective emissivity, the complete surface temperatures in the case c, d1 and d2 were used. The rooftop temperature (Tr) is 328.56 K, street temperature (road) (Ts) is 316.64 K, and wall temperature (Tw) is 304.94 K respectively in a built-up area of Kowloon peninsula from high resolution thermal image. These component temperatures were used as the input in the TUF-3D model (case d1). In order to investigate the effect of heterogeneous thermal distribution for the radiative transfer, the rooftop temperature then was defined as 304.94 K and the wall temperature was defined as 328.56 K to simulate the upwelling radiation and the complete exitance (case d2). and the respective setups for the experiments or sub-experiments for comparison between IUEM-SVF and TUF-3D are listed in the Table 1.

3.4 Application of IUEM-SVF

According to Lagouarde et al. (2012), the nighttime thermal infra-red anisotropy remains lower than 1 K for zenith viewing angles up to 50°, and nighttime anisotropy is insensitive to the azimuth viewing direction. This is because the component temperatures are rather similar, and thus such targets can be taken as isothermal. Our numerical experiments (a1) through (d2) explore a broader range of cases than the one applying to the observations by Lagouarde et al. (2012). The winter nighttime ASTER data acquired on December 16th 2015, 14:36 (UTC) was used to retrieve the land surface temperature. The effective emissivity was estimated for each pixel by applying IUEM-SVF and then it was applied to retrieve the urban surface radiometric temperature from the band 13 of ASTER 2B01 product. Equation 8 was used to retrieve the radiometric surface temperature from band 13 ASTER 2B01 at-surface radiance product. The atmospheric effect was neglected since the ASTER radiance product 2B01 is the derived ground radiance with minimizing the atmospheric effect. The $v_{sky}(i)$ and $v_{adj}(i)$ were calculated using the DSM Lidar data and the building GIS data, as described by Yang et al. (2015b) and Zakšek et al. (2011). Two sets of SVF for only calculating within a pixel and considering the effects from adjacent pixels were generated as described by Yang et al. (2015b).

The radiometric surface temperature retrieved was then compared with the LST product ASTER 2B03 based on the Temperature and Emissivity Separation method (TES). This algorithm is based on a relationship derived from spectral libraries between the minimum value of spectral emissivity and its spectral variance to estimate the emissivity in each ASTER band. While the geometry effect changes the spectral emissivity in urban areas, the limitation of the TES application in urban surface temperature retrieval was analyzed based on the comparison between these LSTs.

Additionally, considering the effective emissivity calculated as the area-weighted average of the component emissivity without considering geometry effect in case b) of section 3.3, the retrieved urban surface temperature under this condition was also evaluated. An overview of the application of IUEM-SVF for urban surface temperature retrieval is shown in Figure 2.

"Insert Figure 2 here"

4. Results

4.1 Comparison between the IUEM-SVF and TUF-3D

a) Figure 3 compares the effective emissivities derived from TUF-3D with those derived from IUEM-SVF, when the components (e.g. rooftop, street and wall) in the domain have same temperature and material emissivity. The effective emissivity derived from IUEM-SVF is similar to the effective emissivity derived from the TUF-3D model, with a correlation coefficient r^2 of 0.99, and RMSDs of 0.004, 0.003, 0.002 and 0.002 when material emissivity is 0.80, 0.85, 0.90 and 0.95 respectively (Cases a1 to a4 in Table 1). This indicates that the IUEM-SVF model can provide an accurate estimation of the effective emissivity when all pixel elements have the same temperature and material emissivity.

"Insert Figure 3 here"

b) The plan area index was set as 0.25 in the simplified configuration of TUF-3D. In this condition, the area-weighted average of the component emissivity without considering geometry does not change with increasing building height. On the contrary, the effective emissivity based on the TUF-3D radiative fluxes increases with increasing building height (decrease of SVF). In the experiment with uniform surface temperature and material emissivities for all facets (Case a1 in Table 1), the difference between these two sets of emissivities can reach 0.10 when the material emissivity is assumed as 0.8 and the difference is about 0.03 when the material emissivity is assumed as 0.95. When the rooftop emissivity was set as 0.945 and street emissivity was set as 0.948 (e.g. same with the ASTER band 13) (Case b in Table 1), the area-weighted mean emissivity of a horizontal surface was 0.947. The effective emissivity from TUF-3D increased with the decrease of SVF, thus the difference between the effective emissivity from TUF-3D and the area-weighted mean emissivity of a horizontal surface increased. When the H/W (SVF) is 4 (0.59) in the simplified configuration of TUF-3D, the difference between these two sets of emissivities was about 0.02. The high-rise buildings and narrow streets of Hong Kong yields H/W larger than 4 in many cases, thus the difference between the average of horizontal surface emissivity and the effective emissivity will be larger.

c) In the Case c of Table 1, the upwelling radiation and the complete exitance, derived from TUF-3D, were both used to calculate the effective emissivity. First the material emissivities of the mixed pixels were calculated as the area-weighted average of the component material emissivities of horizontal surfaces and vertical walls, then the effective emissivity was calculated by applying IUEM-SVF with these material emissivities and SVF. The RMSD between the effective emissivity based on upwelling radiation of TUF-3D and IUEM-SVF is 0.010. This result shows that the heterogeneity of material emissivity has small implication on the effective emissivity in ASTER band 13. If the effective emissivity derived from TUF-3D is calculated as the ratio of the complete exitance of all facets to the Stefan-Boltzmann emittance at the complete surface temperature, the RMSD with IUEM-SVF is 0.018 (Figure 4).

"Insert Figure 4 here"

d) The upwelling radiation and the complete exitance, calculated by TUF-3D, were also used to calculate the effective emissivity. The results showed that the difference between the IUEM-SVF and TUF-3D effective emissivity based on the upwelling radiation and the complete surface temperature becomes large (RMSD = 0.063), when the surface temperature heterogeneity in a mixed pixel is large, e.g. the rooftop temperature (Tr) is 328.56 K, street temperature (road) (Ts) is 316.64 K, and wall temperature (Tw) is 304.94 K (Figure 5) (Case d1 in Table 1). The effective emissivity determined as the ratio of the mean upwelling radiance to the emittance at the complete surface temperature which is the total direct emittance of all facets, however, is even larger than 1 in some cases (Figure 5). As explained in section 3.3, this is caused by the upwelling radiation not including the exitance of all vertical facets. The wall temperature is lower than the rooftop temperature in this case, thus the complete temperature decreases when the fraction of wall increases with increasing H/W (or decreasing SVF). Vertical facets contribute to directional radiance travelling vertically through direct emission and multiple reflection and this does not linearly depend on increasing of wall areas. The contributions to exitance at a horizontal surface by the building rooftop and street fractions do not change with increasing H/W, thus their contribution to the radiance observed by a narrow IFOV, nadir-viewing imaging radiometer remains constant when H/W changes. This is not consistent with the change of complete temperature caused by the increase of the H/W. In order to evaluate the thermal heterogeneity, the wall temperature is defined as higher than rooftop temperature (e.g. the rooftop temperature (Tr) is 304.94 K, street temperature (road) (Ts) is 316.64 K, and wall temperature (Tw) is 328.56 K) (Case d2 in Table 1). In this condition, the complete temperature increases with increasing H/W, but the contribution to the upwelling radiation due to multiple reflection does not agree well with the increases of the complete temperature. The effective emissivity based on the upwelling radiation decreases with increasing H/W (Figure 6). The effective emissivity derived from the ratio of the complete exitance of all facets to the emittance at the complete surface temperature is smaller than 1, and not sensitive to the thermal heterogeneity (Figure 4, 5 and 6). The RMSD between the effective emissivity derived from IUEM-SVF and TUF-3D is 0.018.

“Insert Figure 5 and Figure 6 here”

Results show that urban geometry should not be neglected and estimating emissivity using an area-weighted approach without geometry effect would give a large error in a dense built-up area. When the pixel is thermally heterogeneous, the deviation between the effective emissivity determined as the ratio of observed (line of sight) exitance to the emittance at the complete surface temperature and the effective emissivity determined by IUEM-SVF is large (e.g. 0.063). When the pixel is isothermal, the deviation is small (e.g. 0.010) due to the factor of material heterogeneity only. The complete exitance is not the radiance observed by the remote sensor. A nadir-viewing radiometer captures only total upward exitance, but cannot observe all facets with consideration of thermal heterogeneity of the target. An imaging radiometer with multi-angular capability can thus be used to improve the sampling of the thermal heterogeneity of the urban surface and retrieval of the radiometric surface temperature in urban areas.

4.2 Application of IUEM-SVF and retrieval of the surface radiometric temperature

In order to evaluate the importance of considering geometry effect in estimating effective emissivity, two cases were tested: a) weighted average of component emissivity without considering geometry effect and b) using the IUEM-SVF method. In case (b), the SVF was determined in two ways: (b1) where the SVF is calculated and limited within the coverage of an ASTER pixel (90 m x 90 m); and (b2) where adjacent pixels are taken into account during SVF calculation. The SVF based on b1 was used to input into the calculation of effective emissivity based on IUEM-SVF and separate the effect of neighboring pixels. The map of SVF (b1) (Figure 7a) shows higher values than the map of SVF (b2) (Figure 7b). Figure 7c is the difference of two SVF maps and the difference of these two SVF maps over built-up areas is higher than that over flat areas. The difference between two sets of SVFs range from 0.0 to 0.20 with mean value of 0.074 (Figure 7d).

First, emissivity was estimated using the area-weighted average approach with component emissivities and without considering geometry effect (Figure 8a). This emissivity was calculated for ASTER band 13 using land use and land cover data, building GIS data, the ASTER spectral emissivity library and applied to a flat surface. Figure 8b shows the material emissivity for ASTER band 13 of the complete facets and Figure 8c shows the effective emissivity for ASTER band 13 calculated with Equation 9.

“Insert Figures 7 and 8 here”

Second, the surface radiometric temperature was retrieved by applying the single channel method to ASTER band 13 data and using different sets of effective emissivity data. The difference in LST between the retrieval based on IUEM-SVF (Figure 9b) and the ASTER 2B03 LST product (Figure 9a) is much smaller than the difference in LST between the retrieval without geometry effect (Figure 9c) and the ASTER 2B03 LST product (Figure 9a). The histogram of the differences (Figure 9d) illustrates the impact of the effective emissivity on retrieved LST. The LST without considering geometry effect is much higher than the ASTER 2B03 LST product (mean difference about 1.72 K) and the LST with geometry effect (mean difference about 1.7 K). Thus the most values of the differences between the LST without geometry effect and the other two sets of LSTs are positive and these differences can reach 2 to 3 K (Figure 9d). The spatial pattern of the LST without considering geometry is significantly different from the ASTER 2B03 LST product, while the spatial pattern of the LST with geometry effect is similar to the ASTER 2B03 LST product. The difference between the LST with geometry effect and ASTER 2B03 LST product ranges from -2 K to 2 K and the RMSD between these two kind of LST is about 0.91 K. The temperature in built-up areas is higher than the flat impervious areas (Figure 9a to c).

The difference between the ASTER data product and the LST with geometry effect is not very large because the retrieval of emissivity from the spectral radiance (TES) accounts for at least part of the geometry effects, although the material emissivity is used to construct the relation between the minimum spectral emissivity and the maximum minimum difference ($\varepsilon_{\min}$-*MMD*). This difference is due to the estimation of the material emissivity on the basis of land cover. The empirical relationship between the minimum spectral emissivity and the maximum minimum difference ($\varepsilon_{\min}$-*MMD*) is an error source since this relationship was established by analyzing 86 laboratory TIR emissivity spectra data (Gillespie et al., 1998), and they do not take the geometry factor into account. Moreover, these materials are different from building construction materials in urban areas (e.g. glass, metal). Payan and Royer (2004) demonstrated that urban metals do not follow these empirical relationships, and nowadays more and more new materials and metals are used in the construction industry. Additionally, the geometry effect changes the spectral contrast, e.g. due to the geometry effect, the effective spectral emissivity in the high density urban space tends to 1 and the spectral contrast tends to 0. Thus the empirical relationship between the minimum emissivity and spectral contrast does not necessarily apply to high density urban areas.

"Insert Figure 9 here"

5. Discussion

The complex geometry of urban surfaces has significant implications in the retrieval of temperature over urban areas (Voogt, 1995; Voogt, 2008; Lagouarde et al., 2010). This study focused on the multiple reflection due to the geometry effect over the built-up space, and analyzed the relationship between upward radiance and the urban surface temperature. The performance of IUEM-SVF was evaluated with the TUF-3D model. When the component material and surface temperature are uniform, the IUEM-SVF model estimates the effective emissivity accurately. This implies that the upward radiance of the urban canopy significantly relates to the complete surface temperature in the IUEM-SVF, under the assumption that the pixel is homogenous. When the pixel is thermally heterogeneous, the difference between the effective emissivity derived from the upward radiance of TUF-3D and complete surface temperature and the effective emissivity derived from IUEM-SVF becomes larger and this difference changes with the thermal distribution of the facets. The upward radiance observed by nadir remote sensor is just a part of the total exitance from all facets and it is the result of the complex radiative interactions of different facets within a pixel, while the complete surface temperature is just the simple linear area-weighted average of component temperatures. Both models evaluated in this study have limitations: TUF-3D only works with simple urban geometry without considering spatial variety, and IEUM-SVF does not consider the differences in component temperatures within a grid cell (pixel). Thus the IEUM-SVF still requires further evaluation in the future study.

Lagouarde et al. (2010) and Lagouarde et al. (2012) investigated anisotropy during both nighttime and daytime over Marseille and Toulouse, France and their experimental results showed that the differences in surface brightness temperature vary between -5 and 7 K between nadir and off-nadir measurements in daytime. However, the nighttime thermal infra-red anisotropy remains lower than 1 K when zenith viewing angle up to 50°, and the nighttime anisotropy is insensitive to the azimuth viewing direction. This is because the nighttime difference between the component temperatures is much smaller than in daytime, and the primary forcing for directional anisotropy is zenith viewing angle, and not azimuth viewing angle (in contrast to daytime when the sun generates strong azimuthal temperature variation). Compared with the material emissivity based on classification method or simply linear mixing of the component emissivities in mixed pixel, the IUEM-SVF model improves the effective emissivity estimation and reduces the errors in retrieval of urban surface temperature when the pixel is isothermal or close to isothermal. Accordingly, retrieval of urban surface radiometric temperature is much easier with radiometric data observed in nighttime and IUEM-SVF can be used to derive effective emissivity and further retrieve urban surface radiometric temperature with promising performance.

When the pixel is heterogeneous, the thermal heterogeneity within a mixed pixel in urban areas has a significant impact on the exitance measured by a remote sensor, thus the errors of retrieved surface temperature for summer daytime data would be larger and the retrieved surface temperature from remote sense requires better physical interpretation. One solution is to consider the radiative transfer among the components in the heterogeneous mixed pixel, however, this is challenging due to the low spatial resolution of satellite TIR data, which do not capture the temperature distribution in a mixed pixel. The direction of observation can also be taken into account to retrieve the surface radiometric temperature, and data obtained from off-nadir sensor provide information of the vertical facets over urban areas, which may provide supporting information to retrieve urban complete surface radiometric temperature for the urban energy heat flux estimation. When the IUEM-SVF is used to retrieve the urban surface temperature under the condition of thermal heterogeneity, the geometry effect on effective emissivity can be considered. It can reduce the bias of the retrieved urban surface temperature, derived from the emissivity based on classification and assuming horizontal surfaces. The surface temperature retrieved from IUEM-SVF considers all facets within a pixel and this is not just a simple linear mixture of different components. It is also different from the complete surface temperature. In addition, considering the complexity of urban surface temperature retrieval, validation of the output surface temperature from satellite data is still a challenge and this will be studied in near future.

For the application of the TES algorithm for ASTER in urban areas, the urban geometry effect makes the spectral contrast of the urban canopy different from the material spectra and a flat surface. One solution is to establish a new relationship for different urban geometry characteristics and surface materials using geometrical parameters such as SVF and/or H/W.

6. Conclusion

This study improved UEM-SVF model (now the IUEM-SVF model) by considering the effect of 3-D urban geometry, not only in terms of the cavity effect on emission, but also on reflection by the facets within a pixel. The IUEM-SVF was further evaluated with the micro-climate radiative transfer TUF-3D model. The IUEM-SVF shows promising results when the pixel is thermally homogeneous: in this case the RMSDs between the effective emissivity derived from IUEM-SVF and TUF-3D are 0.004, 0.003, 0.002 and 0.002 when the material emissivity is 0.80, 0.85, 0.90 and 0.95 respectively. This implies that the observed exitance of the urban canopy can be related to the surface radiometric temperature under the assumption that the pixel is uniform in material composition and thermal status. When the pixel is heterogeneous, the difference between the effective emissivity derived from IUEM-SVF and the effective emissivity derived from TUF-3D is larger. When the IUEM-SVF is used to retrieve urban surface temperature under the thermally heterogeneous condition, e.g. summer daytime, the bias can be reduced compared with using the emissivity based on classification. The retrieved urban surface temperature is a summarized value including the interaction among horizontal surfaces and vertical facets. Although IUEM-SVF can be applied to retrieve the urban surface radiometric temperature, and is outperformed on nighttime image, it still requires some further evaluation in the near future. The Temperature and Emissivity Separation (TES) algorithm of ASTER based on the $\varepsilon_{\min}$-*MMD* relationship of the material emissivity may cause bias for retrieval of urban surface temperature, and this bias depends on the geometry characteristics of the built-up space. The $\varepsilon_{\min}$-*MMD* relationship can be reconstructed by considering urban geometry effect and can further be applied to the ASTER TES algorithm in order to retrieve accurate urban surface radiometric temperature.

Acknowledgements

This work was supported in part by the grant of Early Career Scheme (project id: 25201614) from the Research Grants Council of Hong Kong; the grant G-YM85 from the Hong Kong Polytechnic University.The authors thank the Hong Kong Planning Department, Hong Kong Lands Department, the Hong Kong Civil Engineering and Development Department, Hong Kong Observatory and Hong Kong Government Flying Service for the planning, building GIS, weather and climate, and airborne Lidar data, and NASA LP DAAC for the Landsat satellite imagery. Massimo Menenti acknowledges the support of grant P10-TIC-6114 by the Junta de Andalucía.

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