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A novel method to obtain three-dimensional urban surface temperature from ground-based thermography

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ABSTRACT

Urban geometry and materials combine to create complex spatial, temporal and directional patterns of longwave infrared (LWIR) radiation. Effective anisotropy (or directional variability) of thermal radiance causes remote sensing (RS) derived urban surface temperatures to vary with RS view angles. Here a new and novel method to resolve effective thermal anisotropy processes from LWIR camera observations is demonstrated at the Comprehensive Outdoor Scale MOdel (COSMO) test site. Pixel-level differences of brightness temperatures reach 18.4 K within one hour of a 24-h study period. To understand this variability, the orientation and shadowing of surfaces is explored using the Discrete Anisotropic Radiative Transfer (DART) model and Blender three-dimensional (3D) rendering software. Observed pixels and the entire canopy surface are classified in terms of surface orientation and illumination. To assess the variability of exitant longwave radiation (M_{LW}) from the 3D COSMO surface (M_{LW}^{3D}), the observations are prescribed based on class. The parameterisation is tested by simulating thermal images using a camera view model to determine camera perspectives of M_{LW}^{3D} fluxes. The mean brightness temperature differences per image (simulated and observed) are within 0.65 K throughout a 24-h period. Pixel-level comparisons are possible with the high spatial resolution of M_{LW}^{3D} and DART camera view simulations. At this spatial scale (< 0.10 m), shadow hysteresis, surface sky view factor and building edge effects are not completely resolved by M_{LW}^{3D}. By simulating apparent brightness temperatures from multiple view directions, effective thermal anisotropy of M_{LW}^{3D} is shown to be up to 6.18 K. The developed methods can be extended to resolve some of the identified sources of sub-facet variability in realistic urban settings. The extension of DART to the interpretation of ground-based RS is shown to be promising.

1. Introduction

Urban surface temperature (T_s) plays a significant role in the urban surface energy balance as it is central to longwave radiation (LW), turbulent sensible heat and storage heat fluxes. Remote sensing (RS) methods have the potential to provide T_s at large spatial scales for understanding exchanges of sensible heat (e.g. Voogt and Grimmond, 2000; Xu et al., 2008), the thermal comfort of city dwellers (Thorsson et al., 2004), and the urban surface heat island phenomenon (Huang et al., 2016; Kato and Yamaguchi, 2005; Roth et al., 1989). Two major challenges of urban thermal RS observations relate to the complex three-dimensional (3D) urban surface form and material heterogeneity, both causing large spatiotemporal variability of T_s (Voogt and Oke, 2003). Spatiotemporal variability of T_s is influenced by the relative orientation of surfaces to the sun during the day, and sky at night (Voogt and Oke, 2003). The diversity of thermal and radiative properties of surface materials causes additional variability (Voogt, 2008). What results is a directional variability, or an effective thermal anisotropy (Krayenhoff and Voogt, 2016), of broadband longwave radiation (M_{LW}, W m^{-2}) from the urban canopy surface. The anisotropic behavior of urban canopies is defined as "effective" to differentiate from thermal anisotropy exhibited by individual surface components (Voogt and Oke, 1998). Effective thermal anisotropy clearly affects satellite measured radiance, which is indicative of satellite derived longwave radiation

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(M_{LW}^{RS}). As a result, the apparent T_s can vary depending on view direction. M_{LW}^{RS} can be described by:

$$M_{LW}^{RS} = \sum_{i}^{n} M_{LW,i} f_i \tag{1}$$

where $M_{LW,i}$ is the exitant broadband longwave radiation from a given canopy surface element i that comprises fraction f of the instrument field of view (FOV). Out of the total number of canopy surface elements n, $M_{LW,i}$ may be unique due to the highly variable radiative properties associated with its surface temperature, emissivity (ε) and contributions from longwave reflections. M_{LW}^{RS} is also sensitive to urban canopy geometry and to the specific view angle within each image swath. These factors combine to form a view angle specific f_i which translates to a view angle specific value of M_{LW}^{RS}. For example, f_i for roof and tree tops is generally overemphasised within M_{LW}^{RS} for urban areas (Roth et al., 1989). Corrections of effective thermal anisotropy are critical when retrieving high-quality T_s products for urban environments at large spatial scales from satellite-derived M_{LW}^{RS}.

The impact of effective thermal anisotropy on M_{LW}^{RS} has been studied using various observation and modelling techniques. Observations from airborne platforms (e.g. Lagouarde et al., 2004; Sugawara and Takamura, 2006; Voogt and Oke, 1998) allow highly variable view angles at scales representative of satellite pixel resolutions (100 m–1 km). However, cost and air traffic restrictions usually limit these to short-term research campaigns. As obtaining different view angles requires multiple flyovers (i.e. difficult to conduct simultaneously), sequential flyovers with one aircraft may temporally confound results. Thus, the directional variability of M_{LW}^{RS} at a micrometeorological timeframe (sub-hourly) for energy exchange processes (Christen et al., 2012) may be unresolved. Ground-based RS observations are interesting in that M_{LW} can be resolved at high temporal resolutions (e.g. Christen et al., 2012) while resolving the individual facet (e.g. roof, wall) and sub-facet scale classes of $M_{LW,i}$ that constitute the structural and radiative characteristics of the urban canopy. For ground-based RS, a challenge is to sample enough facets representative of the complete 3D urban canopy at any one time. A single ground-based measurement provides a highly directional sample at high spatial resolution. Several ground-based sensors are required to sample facets of all orientations, unless a single ground-based sensor is operated on a rotating (e.g. Adderley et al., 2015) or mobile (e.g. Voogt and Oke, 1997) platform. As satellite based RS is also inherently biased by FOV, it is important to be able to understand the nature of this bias.

Modelling can further help resolve the contribution of sub-facet scale variability of M_{LW} on effective thermal anisotropy. The nature of effective thermal anisotropy and M_{LW}^{RS} can be understood under constrained conditions at high temporal and spatial resolutions. Therefore, modelling is considered key to progress (Voogt, 2008; Voogt and Oke, 2003). Approaches typically involve a parameterisation of surface geometry, an energy balance model prescription of surface temperature and sensor view modelling of M_{LW}^{RS} to resolve $M_{LW,i}$ and f_i (Eq. 1) for a given surface-sensor viewing geometry. Surface temperatures can be prescribed from 2D (Kusaka et al., 2001; Sugawara and Takamura, 2006; Voogt, 2008), 2.5D infinite street canyon (e.g. Lagouarde et al., 2010) and 3D (Krayenhoff and Voogt, 2007, 2016; Soux et al., 2004) energy balance simulations to estimate $M_{LW,i}$ (Eq. 1) at facet (e.g. surface orientation, roof, ground) or sub-facet (e.g. insolation, material) scales.

Few sensor-view modelling studies exist that prescribe $M_{LW,i}$ from observations at facet and sub-facet scale, despite this complementing and constraining energy balance simulations. Classifying surfaces within ground-based RS source areas poses challenges because of the potentially diverse viewing geometries, complex 3D urban canopy structure, and low resolution of longwave infrared (LWIR) camera imagery. Previously, the spatial frequency distributions of M_{LW} determined by ground-based LWIR imagery were used to infer canopy surface classes (e.g. Voogt and Grimmond, 2000) or surface classes were manually identified and extracted (e.g. Voogt, 2008). Manual approaches based on broadband thermal imagery are limited when the temperature contrast between facets is low (because of orientation or material properties). Information at multiple wavelengths can be valuable to improve classification. With maturing of sensor view modelling, it is becoming a powerful tool to objectively classify surface elements captured by RS imagery. Previous studies interpreting ground-based LWIR imagery have determined per-pixel path lengths for atmospheric correction of observations from on top of a high-rise building in Berlin (Meier et al., 2011). The SUM surface-sensor-sun model (Soux et al., 2004) enables sensor view modelling of $M_{LW,i}$ prescribed from observations, limited to urban surface geometry resolved as regular arrays of rectangular shaped buildings. Studies using SUM have prescribed temperatures intermittently (e.g. Voogt, 2008) from ground-based and airborne platforms observations. 3D rendering and editing software and a 3D vector model have facilitated the classification of ground-based LWIR imagery in a suburban area in Vancouver (Adderley et al., 2015). Here, classified temperature "textures" were gap-filled to enable extrapolation across the 3D vector model as a complete brightness temperature product for sensor view modelling of hemispherical radiometer measurements using a single LWIR camera on a rotating mast.

In the current study, a flexible observational and modelling approach is developed to prescribe M_{LW} from broadband longwave radiation fluxes derived from static ground-based LWIR camera observations. A 3D distribution of exitant broadband longwave radiation (M_{LW}^{3D}, W m^{-2}) is constructed from observations. The approach involves a novel method to classify each camera image. Pixels within each image are associated with a specific surface class prior to observations being extrapolated to all urban canopy surface elements in 3D. A "model world" (MW) is used to process and interpret observations which enables "real world" (RW) surfaces to be related to each camera image by camera view modelling. It provides a robust and quantitative method to interpret observations. Surface class i is determined in 3D space [i.e. i (X, Y, Z)] and is then accurately mapped to the 2D (x, y) coordinates of a camera image plane (IP) [i.e. $i(x, y)$].

Unique here is the camera view modelling used to interpret observations, as surface classes are determined at high temporal and spatial resolution using surface geometry and shortwave (SW) radiative characteristics for each time step. This is designed to ensure all canopy surfaces are always accounted for when extrapolating observations over the 3D urban surface. A potential constraint of highly directional ground-based measurements is turned to an advantage by positioning two cameras at opposing view angles. This permits a combined observational source area representative of all surface classes that constitute the 3D urban surface. Extrapolated observations are compared with original camera imagery. This is done by projecting the extrapolated observations through the perspective of simulated cameras, with modelled perspectives matching those seen by the original camera imagery. This approach is unique in that the modelled perspectives are shown to reproduce the perspectives of the original imagery at pixel level and to a high degree of accuracy. Extrapolated observations have potential as a tool for further sensor view modelling to explore the impact of effective thermal anisotropy on directionally variable M_{LW}^{RS} products for any given surface-sensor configuration.

The observational setup (Section 2.1, Section 2.2), the classification methods (Section 2.3, Section 2.4) and extrapolation (Section 3) of observations are introduced. Results (Section 4) include evaluation of proposed methods and demonstrate their benefits for application in urban RS. It is concluded (Section 5) that the detailed modelling approach provides a valuable tool for future studies in real city settings.

2. Methods

LWIR camera observations are interpreted and estimated as M_{LW}^{3D} in a MW environment (Fig. 1). Two LWIR cameras (Section 2.2) were