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Enhancing the spatial resolution of satellite-derived land surface temperature mapping for urban areas

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ABSTRACT

Land surface temperature (LST) is an important environmental variable for urban studies such as those focused on the urban heat island (UHI). Though satellite-derived LST could be a useful complement to traditional LST data sources, the spatial resolution of the thermal sensors limits the utility of remotely sensed thermal data. Here, a thermal sharpening technique is proposed which could enhance the spatial resolution of satellite-derived LST based on super-resolution mapping (SRM) and super-resolution reconstruction (SRR). This method overcomes the limitation of traditional thermal image sharpeners that require fine spatial resolution images for resolution enhancement. Furthermore, environmental studies such as UHI modelling typically use statistical methods which require the input variables to be independent, which means the input LST and other indices should be uncorrelated. The proposed Super-Resolution Thermal Sharpener (SRTS) does not rely on any surface index, ensuring the independence of the derived LST to be as independent as possible from the other variables that UHI modelling often requires. To validate the SRTS, its performance is compared against that of four popular thermal sharpeners: the thermal sharpening algorithm (TsHARP), adjusted stratified stepwise regression method (Stepwise), pixel block intensity modulation (PBIM), and emissivity modulation (EM). The privilege of using the combination of SRR and SRM was also verified by comparing the accuracy of SRTS with sharpening process only based on SRM or SRR. The results show that the SRTS can enhance the spatial resolution of LST with a magnitude of accuracy that is equal or even superior to other thermal sharpeners, even without requiring fine spatial resolution input. This shows the potential of SRTS for application in conditions where only limited meteorological data sources are available yet where fine spatial resolution LST is desirable.

1. Introduction

The majority of the global population resides in urban areas and the urban population is expected to further increase to more than 3 billion people by 2050 (Buhaug & Urdal, 2013). Cities are a focal point for economic and social activities and, therefore, are closely related to human daily life (Madlener & Sunak, 2011; Mirzaei & Haghighat, 2010). Attention is increasingly being given to the pursuit of more comfortable living conditions in urban areas in the face of increasing urbanisation. There is, therefore, growing interests in the factors that impact on human comfort and well-being in cities (Gago, Roldan, Pacheco-Torres, & Ordóñez, 2013; Kleerekoper, Van Esch, & Salcedo, 2012; Oke, 1982; Quattrochi & Luvall, 1999; Santamouris, 2013).

Many researchers have shown that the temperature of an urban area is generally higher than that of its surroundings (Gago et al., 2013; Mirzaei & Haghighat, 2010). This phenomenon is known as the urban heat island (UHI) and this can be detrimental to human comfort. For instance, UHIs are often linked to poor air quality (Sarrat, Lemonsu, Masson, & Guedalia, 2006), and they can increase the energy demand of cities (Kolokotroni, Ren, Davies, & Mavrogianni, 2012; Maria Kolokotroni, Zhang, & Watkins, 2007; Kondo & Kikegawa, 2003; Mirzaei & Haghighat, 2010; Santamouris et al., 2001). UHIs can even contribute to human mortality rates, with thousands of heat-related deaths in cities every year (Ashley et al., 2008; Cleveland, 2007; Gosling, Lowe, McGregor, Pelling, & Malamud, 2009). For example, some 50,000 deaths were caused by the 2003 European heat wave (Mirzaei & Haghighat, 2010). The UHI has been directly linked to adverse impacts on human health, and human thermal comfort in urban areas is expected to decline with climate change (Cheung & Hart, 2014; Tan et al., 2010). A considerable body of literature reports approaches to relieve the effect

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of the UHI with some initiatives already in operation (Rosenzweig et al., 2006; Schmidt, 2006). However, causes of the UHI can vary from place to place and thus there is no general or global understanding of, or solution for problems associated with, UHIs (Mirzaei & Haghighat, 2010). It is acknowledged that temperature is closely related to land cover and hence much research has focused on this aspect (Weng, 2009). Urban areas represent a highly complex surface type which makes urban surface temperatures highly variable, both temporally and spatially (Prata, Caselles, Coll, Sobrino, & Ottlé, 1995; Vauclin, Vieira, Bernard, & Hatfield, 1982). Constructing high spatial resolution maps of urban temperature is an important first step towards analysing the UHI and in working towards solutions for its negative consequence for humans.

Traditional approaches to collect temperature data for mapping purposes are based upon weather station records and mobile equipment such as thermometers or sensors mounted on vehicles (Borbora & Das, 2014). Such approaches suffer from several major limitations. The spatial resolution of weather station data is, for example, typically very coarse since stations tend to be distributed very sparsely. For example, there are only 34 weather stations which record daily or hourly temperature throughout Greater London, an area of 1572 km^2 (http://badc.nerc.ac.uk/googlemap/midas_googlemap.cgi). Moreover, the temporal coverage of these stations is inconsistent, which means not all of them can be used for any specific date. When it comes to smaller cities such as Nottingham, UK, which covers around 422 km^2, there are only six weather stations recording daily or hourly temperature. Although mobile temperature sensors can address the spatial resolution limitation to some extent by providing more measurements across a city, this approach cannot give a fully synchronised view over the whole city (Weng, 2009), and is also limited in terms of temporal coverage and can be a very costly undertaking.

Because of the problems with traditional methods, interest in remote sensing data for estimating land surface temperature (LST) is increasing as this approach can acquire data across large areas rapidly and regularly and has a much higher spatial sample density than weather station data. However, effective UHI analysis requires detailed and accurate information on urban heat flux and energy dynamics, and the relatively coarse spatial resolution of most spaceborne remote sensing systems may be inadequate for this purpose. For example, the spatial resolution of one of the most widely used thermal image data sources, the Moderate Resolution Imaging Spectroradiometer (MODIS), is 1 km for the thermal bands, and 500 m/250 m for the optical bands. The spatial resolution of other meteorological satellite sensors such as the Geostationary Operational Environmental Satellite (GOES) can be as coarse as 4 km/8 km for the thermal band and 1 km/4 km for the optical bands. It can be noticed that optical bands tend to have finer spatial resolutions than thermal bands because they operate at shorter, more energy-rich, wavelengths. While some visible and near infrared (NIR) satellite sensors can provide imagery with sub-meter resolution, currently the finest spatial resolution of the thermal spaceborne image data is 60 m, provided by the Enhanced Thematic Mapper Plus (ETM+) on board Landsat 7. Although the Landsat 8 was launched in 2013, its thermal sensor has a spatial resolution of only 100 m, even coarser than that of Landsat 7. This relatively coarse spatial resolution may be affected strongly by mixed pixels, whereby each pixel comprises a mixture of two or more land cover types, especially in complex and spatially heterogeneous urban areas. Consequently, any attempt to predict urban LST from spaceborne imagery may suffer from considerable inaccuracy. One solution to this problem may be to use imagery from airborne sensors since these can provide considerably finer spatial resolution data than satellite sensors, but such sources are costly and not routinely available. A more realistic and achievable solution may be offered by 'thermal sharpening' methodologies, whereby fine spatial resolution optical imagery is integrated with coarser resolution thermal imagery to create a finer resolution thermal image output (Dominguez, Kleissl, Luvall, & Rickman, 2011; Zhan et al., 2013). Some such approaches are well-established; the earliest thermal sharpening technique dates back to the 1980s when, for example, Tom et al. (1985) demonstrated such analysis on Landsat TM thermal data.

Various thermal sharpening methods are now available for use, but the accuracy of different methods can vary considerably for different land surface types. Given the major role of vegetation in modulating urban temperatures, most thermal sharpening methods are based on the empirical relationship between the LST and a vegetation index (e.g. the Normalised Difference Vegetation Index (NDVI)). For instance, fine spatial resolution NDVI data derived from optical imagery may be combined with coarser spatial resolution thermal imagery to predict LST at the finer resolution (Essa, Verbeiren, Van der Kwast, Van de Voorde, & Batelaan, 2012). However, the relationship between LST and NDVI can be unreliable under certain conditions such as where study areas have little vegetation present or where atmospheric conditions have high water vapour content (Chen, Yan, Ren, & Li, 2010; Yang, Cong, Liu, & Lei, 2010a). In addition, the surface indices derived from remote sensing data are widely used as predictor variables in urban studies (e.g. UHI). Theoretically, the predictors in an analytical model should be independent (Osborne & Waters, 2002). It might be difficult to achieve absolute independence. However, the predictors for modelling should at least be as independent as possible. If the LST is derived with the aid of a surface index, that index will have a high correlation with the sharpened LST and may no longer be suitable for use as a predictor in a model together with the sharpened LST. This reduces the range of appropriate predictors available for the modelling work, thus limiting analysis. Further significant limitations of most current thermal sharpening methods are their requirement for both coarse and fine spatial resolution data and that the target (sharpened) spatial resolution is determined by the fine resolution input. That is, while it is possible to sharpen the coarse resolution data to a target resolution between that of the coarse and fine spatial resolution data, it is impossible to sharpen the coarse resolution data to a target resolution which is finer than the available fine resolution data. Additionally, while some sensors do acquire both fine resolution optical imagery and coarse resolution thermal imagery simultaneously (e.g. Landsat ETM+), this is not always the case. Where land cover changes slowly the optical and thermal data may not need to be strictly simultaneous. In this case, the data from different satellite sensors may be used. However, if a very fine spatial resolution (≤30 m) is required, the optical data is generally costly. In this paper, a method is proposed to enhance the spatial resolution of satellite-derived LST maps that does not require a fine resolution input and does not rely on any surface indices to sharpen the LST. It is based on two image processing techniques which could be used to enhance image spatial resolution: super-resolution mapping (SRM) and super-resolution reconstruction (SRR). Previous studies on SRM have focused on enhancing the spatial resolution of land cover maps obtained from remotely sensed imagery. In this paper, SRM is used to enhance the spatial resolution of image-derived emissivity maps, one of the variables required to estimate LST from remotely sensed data. SRR has been widely used to generate a fine spatial resolution image by using a set of coarse spatial resolution images. This approach seeks to use the sub-pixel shifts between all the scenes to accumulate more detailed spatial information on the imaged area. Here, SRR has been used to enhance the spatial resolution of both the thermal radiance derived from the original satellite sensor image and atmospheric profiles involved in LST estimation which can either be derived from satellite sensor data or from other sources. This is achieved without use of a vegetation index. Otherwise, many urban studies do not require