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Downscaling of thermal images over urban areas using the land surface temperature–impervious percentage relationship

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ABSTRACT

Intensive expansion and densification of urban areas decreases environmental quality and quality of urban life as exemplified by the urban heat island effect. For this reason, thermal information is becoming an increasingly important data source for integration in urban studies. It is expected that future spaceborne thermal sensors will provide data at appropriate spatial and temporal resolutions for urban studies. Until they become operational, research has to rely on downscaling algorithms increasing the spatial resolution of relatively coarse resolution thermal images albeit having a high temporal resolution. Existing downscaling algorithms, however, have been developed for sharpening images over rural and natural areas, resulting in large errors when applied to urban areas. The objective of this study is to adapt the DisTrad method for downscaling land surface temperature (LST) over urban areas using the relationship between LST and impervious percentage. The proposed approach is evaluated by sharpening aggregated LST derived from Landsat 7 ETM+ imagery collected over the city of Dublin on May 24th 2001. The new approach shows improved downscaling results over urban areas for all evaluated resolutions, especially in an environment with mixed land cover. The adapted DisTrad approach was most successful at a resolution of 480 m, resulting in a correlation of R^2 = 0.84 with an observed image at the same resolution. Furthermore, sharpening using the adapted DisTrad approach was able to preserve the spatial autocorrelation present in urban environments. The unmixing performance of the adapted DisTrad approach improves with decreasing resolution due to the fact that the functional relationship between LST and impervious percentage was defined at coarse resolutions.

1. Introduction

In 1950 30% of the world's population was living in urban areas, while this value will increase to 60% in 2030 (Golden, 2004). The growing population in urbanized areas causes an increase of anthropogenic heat. As a result the core of cities in temperate climate zones becomes warmer than their periphery, thus forming an urban heat island (UHI) (Voogt and Oke, 2003), which has an impact on the microscale and mesoscale climate. Heat-related morbidity and mortality are among the primary health concerns and are expected to increase as a result of climate change that increases the UHI effect (Johnson and Wilson, 2009).

The UHI intensity is influenced by local and synoptic weather, season, time of day, size of the city and its geographical location, urban morphology, and anthropogenic heat (Kim and Baik, 2005). Therefore, a range of spatial and temporal scales should be considered in UHI studies. One of the great challenges for current UHI studies is how to support this research with techniques to retrieve land surface temperature data with high temporal and spatial resolution. This data has to support the scientific and policy makers' community in understanding impacts, both positive and negative, to set policies for mitigating those impacts or to develop indicators to address the UHI effect within a sustainable development context. Therefore land surface temperature is a physical parameter of prime importance for a wide variety of scientific urban studies. In urban climatology, land surface temperature is the key input parameter used in algorithms estimating net radiation, sensible and latent heat flux, thermal inertia, surface urban heat island intensity, perceptible water, evapotranspiration, urban-induced surface runoff and surface moisture (Stathopoulou and Cartalis, 2009). Various spaceborne thermal sensors provide

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useful information for urban studies. The choice of an appropriate sensor is currently a trade-off between spatial and temporal resolution: sensors with a high temporal resolution have a low spatial resolution and vice versa.

Thermal sharpening is a promising technique for enhancing the spatial resolution of mixed pixels acquired by coarse resolution sensors. During the last ten years various thermal sharpening techniques for unmixing land surface temperature have been developed based on land cover. Thermal sharpening methods in remote sensing can be grouped into two categories. The first method, known as the physical downscaling method, is based on establishing a functional relationship between land surface temperature and ancillary data, which satisfies two conditions: (1) the functional relationship is physically meaningful and holds across different resolutions; and (2) the ancillary data can be easily scaled (Zhukov et al., 1999; Kustas et al., 2001; Liu et al., 2006; Agam et al., 2007a,b; Liu and Pu, 2008). The second method, known as the statistical downscaling method is based on the direct estimation of subpixel land surface temperature from higher spatial resolution ancillary data without referring to physical models at different resolutions (Ottlé et al., 2008; Stathopoulou and Cartalis, 2009). Testing of the latter method is still in a preliminary stage for applications in urban areas.

In a previous study Essa et al. (2012) evaluated the relationship between land surface temperature of urban pixels and 15 indices and concluded that the relationship with impervious percentage gives the best results. This conclusion is also in agreement with findings from Yuan and Bauer (2007), who suggest that impervious percentage accounts for most of the land surface temperature variation in urban areas. Furthermore, Essa et al. (2012) and Yuan and Bauer (2007) conclude that there is a strong linear relationship between land surface temperature and impervious percentage, independent of the season of image acquisition. In contrast, the relationship between land surface temperature and NDVI varies with the seasons (Kaufmann, 2003). Therefore, Essa et al. (2012) suggested to use impervious percentage instead of NDVI in the DisTrad sharpening algorithm (Kustas et al., 2001) when applied to urban areas. They demonstrated the improvement for sharpening of a Landsat 7 ETM+ image of Dublin.

Due to the low temporal resolution of Landsat images, the current study evaluates the adapted DisTrad algorithm developed by Essa et al. (2012) for sharpening images with a spatial resolution comparable with daily MODIS land surface temperature products. While in Essa et al. (2012) only 25% of the pixels with the lowest coefficient of variance (CV) within a coarse resolution pixel were used in the regression, this study evaluates different threshold values. Furthermore, a detailed analysis of the spatial autocorrelation of the unsharpened and sharpened products is presented. The images sharpened with the original and the adapted DisTrad algorithm are compared with each other and with non-sharpened images using visual, statistical, and geostatistical analysis methods.

2. Study area and data

This study uses the 60 m resolution land surface temperature image that was derived by Essa et al. (2012) as a basis for deriving coarse resolution images and reference images for evaluation of the sharpening. The image was derived from a Landsat 7 ETM+ scene from May 24th 2001 covering 2700 km^2, bounded by the longitudes 6°00′ and 6°48′W and latitudes 53°07′ and 53°35′N. It covers the urbanized Mid-East of the Greater Dublin region (Fig. 1). This area is characterized by heterogeneous urban landscape patterns, which makes the study area ideal for evaluating the adapted DisTrad procedure.

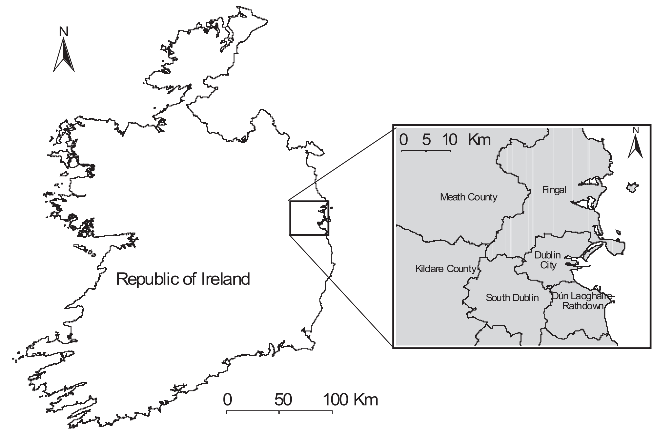

Fig. 1. Ireland with inset figure indicating the study area: the Greater Dublin region.

A 30 m resolution impervious percentage map derived by Van de Voorde et al. (2010) will be used in the regression analysis. More details on the derivation of the impervious percentage map can be found in Van de Voorde et al. (2010).

3. Methodology

3.1. Sharpening experiment

Ideally, the adapted DisTrad approach applied to a coarse resolution land surface temperature product needs to be evaluated with high resolution land surface temperature data acquired at the same moment. Image products from different sensors, however, differ in acquisition time and date, data level, processing algorithms, temporal integration, geometric accuracy, etc. Therefore, in this study a Landsat 7 ETM+ image was aggregated to 960 m resolution and evaluated for downscaling using the approach proposed in Essa et al. (2012). In this way the performance of the algorithm can be optimized and verified in a best case scenario, independent of errors introduced by differences between sensors.

Landsat 7 ETM+ has both VNIR and TIR data at a relatively high resolution acquired at the same date and time. This makes this sensor ideal for evaluating the downscaling, without having to take care of differences between TIR and VNIR channels from different platforms.

The performance of the adapted DisTrad approach using impervious percentage to derive high resolution land surface temperature data over urban areas was evaluated by comparing the sharpened results with the original DisTrad approach using NDVI (Kustas et al., 2001). In addition, a baseline case (UniTrad), representing no sharpening, i.e. no incorporation of high-resolution information, was also determined by assigning each sub-pixel the land surface temperature of the corresponding coarse resolution pixel.

The Landsat 7 ETM+ land surface temperature image, impervious percentage image, and NDVI image were aggregated by a spatial averaging function to images with a resolution of 60, 90, 120, 240, 480, and 960 m, which will be referred to as "observed images". Aggregation using spatial averaging is often used to simulate remote sensing images. Dominguez et al. (2011), for example, aggregated higher resolution ATLAS data (albedo, NDVI and land surface temperature observed at 10 m resolution) for evaluation of the High-resolution Urban Thermal Sharpener (HUTS) method. Agam et al. (2007b) aggregated aircraft data (NDVI and land surface temperature observed at 10 m resolution) for evaluation of the TsHARP method. Both studies used data aggregated to 90 m resolution to simulate ASTER satellite data. In this study the aggregated