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A simplified urban-extent algorithm to characterize surface urban heat islands on a global scale and examine vegetation control on their spatiotemporal variability

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ABSTRACT

We develop a new algorithm, the simplified urban-extent (SUE) algorithm, to estimate the surface urban heat island (UHI) intensity at a global scale. We implement the SUE algorithm on the Google Earth Engine platform using Moderate Resolution Imaging Spectroradiometer (MODIS) images to calculate the UHI intensity for over 9500 urban clusters using over 15 years of data, making this one of the most comprehensive characterizations of the surface UHI to date. The results from this algorithm are validated against previous multi-city studies to demonstrate the suitability of the method. The dataset created is then filtered for elevation differentials and percentage of urban area and used to estimate the diurnal, monthly, and long-term variability in the surface UHI in different climate zones. The global mean surface UHI intensity is 0.85 °C during daytime and 0.55 °C at night. Cities in arid climate show distinct diurnal and seasonal patterns, with higher surface UHI during nighttime (compared to daytime) and two peaks throughout the year. The diurnal variability in surface UHI is highest for equatorial climate zone (0.88 °C) and lowest for arid zone (0.53 °C). The seasonality is highest in the snow climate zone and lowest for equatorial climate zone. While investigating the change in the surface UHI over a decade and a half, we find a consistent increase in the daytime surface UHI in the urban clusters of the warm temperate climate zone (0.04 °C/decade) and snow climate zone (0.05 °C/decade). Only arid climate zones show a statistically significant increase in the nighttime surface UHI intensity (0.03 °C/decade). Globally, the change is mainly seen during the daytime (0.03 °C/decade). Finally, the importance of vegetation differential between urban and rural areas on the spatiotemporal variability is examined. Vegetation has a strong control on the seasonal variability of the surface UHI and may also partly control the long-term variability. The complete UHI data are available through this website (https://yceo.yale.edu/research/global-surface-uhi-explorer) and allows the user to query the UHI of urban clusters using a simple interface.

1. Introduction

The urban heat island (UHI) effect refers to the positive temperature difference between an urban area and its hinterland, and it is one of the most well-known consequences of urbanization on local climate (Souch and Grimmond, 2006). It has been an active area of research in urban climatology since it was first observed a century back by Luke Howard (Howard, 1833). Traditionally, it was defined as the air temperature difference between the urban zone and its surroundings, known as the canopy UHI, and was studied using in-situ weather stations or mobile measurements (Voogt, 2007). The advent of satellite data has allowed us to define a new kind of urban heat island, known as the surface UHI, which is the difference in land surface temperature (LST) between the urban area and its surrounding non-urban area (Rao, 1972). Canopy and surface UHI intensities are similar at the annual scale but may have different diurnal and seasonal variabilities (Cui and De Foy, 2012; Chakraborty et al., 2016).

Urbanization changes the surface energy budget by modifying albedo, reducing evaporative cooling via replacement of vegetated surfaces with built-up surfaces, increasing heat storage due to the higher heat capacity of urban structures, and changing dissipation of heat via modulation of thermal roughness and urban spatial configuration (Goward, 1981; Taha, 1997; Arnfield, 2003; Connors et al., 2013; Zhao et al., 2014; Debbage and Shepherd, 2015). For heavily polluted cities in arid regions, dust particles can trap longwave radiation and increase the nighttime UHI intensity (Cao et al., 2016). Other major determinants of the UHI intensity mentioned in the literature are synoptic conditions, city size, precipitation, humidity, cloud cover, and coastal

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feedback (Santamouris, 2015).

Studies quantifying the magnitude of the UHI effect have been performed for hundreds of cities around the world (Oke, 1979; Arnfield, 2003; Santamouris, 2015). Traditionally, such studies are done on a city-by-city basis, which can lead to inconsistencies due to differences in data collection processes, sensor types, and other methodological considerations. A systematic critique of the UHI literature (Stewart, 2011) found that roughly half of the UHI studies lacked robustness. Some important issues were: not controlling for weather factors, lack of information on site metadata and instrumentation, lack of accounting for temporal variability during mobile surveys, inconsistency in defining both urban and rural measurement locations, and disregarding the effect of scale.

The use of satellite data has reduced the inconsistency in measurement techniques by allowing a standardized data collection approach that can be implemented for multiple cities. Previously, Tran et al. (2006) and Imhoff et al. (2010) used satellite data to investigate the surface UHI of 18 Asian megacities and 38 highly populated US cities, respectively. Systematic studies have also been performed on the UHI intensity of cities in Europe (Schwarz et al., 2011; Zhou et al., 2013). A recent study investigated the diurnality and seasonality of the surface UHI in the 84 largest cities in India (Shastri et al., 2017). The principal works done on multiple cities at the global scale are by Peng et al. (2011), who analyzed the UHI of 419 largest cities using 5 years of MODIS AQUA LST data and Clinton and Gong (2013), who investigated the global pattern of the UHI intensity for 2010.

For both canopy and surface UHI studies, one persistent issue is the definition of the rural station (for canopy UHI) or the boundary between the urban and rural area (for surface UHI) (Martin-Vide et al., 2015). Nearby rural areas are affected by advection from the urban core. However, if the rural station is too far away, local weather changes might be more important than the impact of land use changes. A recent study in China found that the footprint of the UHI can be twice or thrice the area of the city (Zhou et al., 2015). This is much higher than the area of the fixed buffer zones normally used in global UHI studies (Clinton and Gong, 2013). The study also demonstrated that for closely located cities, the effect of advection from other cities could also have an impact on the UHI intensity.

Smaller urban areas have generally been overlooked in the existing UHI literature, which disproportionately focuses on large mega-cities. Moreover, the temporal and seasonal variability of the UHI intensity has not been investigated at a global scale. So in this study, we map the daytime and nighttime surface UHI for all urban areas currently detectable via MODIS-based spectral classification of land use using over 15 years of observed data. Buffer-based analyses of the UHI intensity are common in the literature and it is hard to choose a fixed buffer width that is reasonable for all the cities across the globe. So we develop a new algorithm, the simplified urban-extent algorithm (SUE), that can be used to automatically calculate the UHI intensity at a global scale. The algorithm is implemented on Google Earth Engine, a cloud-based platform for planetary-scale data archiving and geospatial analysis (Gorelick et al., 2017). We estimate the surface UHI intensity for almost 9500 distinct urban clusters and estimate the diurnal, seasonal, and annual pattern of the UHI intensity for each climate zone. Many of the factors that influence the UHI intensity, like urban albedo, longwave trapping by the urban canyon, surface roughness, etc. do not show significant seasonal or temporal variations, given the relatively constant nature of urban areas. The main varying characteristic is vegetation cover, which changes throughout the year, as well as between years. Given the focus on the seasonal and temporal variability of the UHI in the present study, we examine how vegetation controls this dynamic globally, and for different climate zones.

The major research questions investigated in the present study are:

- How well does the newly designed SUE algorithm replicate the known characteristics of the surface UHI effect?
- How does the mean, diurnal, and seasonal patterns of the UHI compare for urban clusters in different climate zones?
- How has the UHI intensity changed in the last decade and a half, both globally and for each climate zone?
- How strongly does vegetation control the seasonal and temporal variability of the surface UHI?

Section 2 describes the SUE algorithm developed for this study. Section 3 shows the comparison of the results with those obtained from previous multi-city studies. Section 4 shows the general results as well as the diurnal, seasonal, and annual variability of the surface UHI for urban clusters in different climate zones. Section 5 examines how vegetation controls the spatiotemporal variability of the UHI and discusses the advantages and disadvantages of the SUE algorithm.

2. Methodology

2.1. The Simplified Urban-Extent (SUE) algorithm

In this study, we define the surface UHI as the difference in LST of the urban pixels and the non-urban pixels within each urban extent, which we call the simplified urban-extent (SUE) algorithm. First, the MODIS-derived LST data from TERRA (MOD11A2) and AQUA (MYD11A2) satellites, available at 1 km × 1 km resolution, are preprocessed, with only the clear-sky pixels with average LST error of less than or equal to 3 K being selected for further analysis. The quality controlled datasets are then used to estimate the LST at 0130, 1030, 1330, and 2230 local time (LT). Data from 2000 to 2017 (18 years) are used from the TERRA platform, while data from 2002 to 2017 (16 years) are used from AQUA.

The urban extent data are from Natural Earth (2018). It is a combination of the global urban land database by Schneider et al. (2009, 2010) and the Oak Ridge National Laboratory's LandScan population database (Dobson et al., 2000). The urban data are based on MODIS measurements for February 2001 to February 2002 and is defined using the C4.5 decision tree algorithm (Quinlan, 1993). This dataset has already been validated, with an overall accuracy of 93%, using a Landsat-based map of 140 urban areas in different ecoregions, and for different levels of population and economic development (Schneider et al., 2010). These global urban data are intersected with Thiessen polygons derived from the LandScan population points to create the urban land database; the results are in vector format on the Natural Earth website (2018). The urban units are closed polygons around contiguous urban agglomerations. Fig. 1 shows an example of one such urban unit consisting of multiple urban areas. The advantage of using this dataset is that it is based on a consistent algorithm implemented on the MODIS land use satellite product and bounds the global hot spots of human habitation.

Fig. 1 shows the steps used to estimate the surface UHI of each urban cluster. Firstly, the global LST and MODIS LU/LC data (at 500 m × 500 m resolution) for 2013 (MCD12Q1) are clipped to the urban extent dataset. Then, two subsets are created, one for urban land use (in red in Fig. 1) and another for all land use other than urban and water based on the land use data. The water pixels are removed since the high specific heat capacity of water would lead to an overestimation of the UHI intensity during the daytime and an underestimation during nighttime. After subsetting, the spatial mean of the LST for both subsets are calculated for each urban cluster and their difference is the surface UHI for that cluster. Before taking the spatial means, the subsetted LST pixels are automatically resampled to 500 m × 500 m grids to match the resolution of the LU/LC data. When calculating the surface UHI for separate years, the same extent shape is applied to all years, though the subsetting is done using the MODIS LU/LC data for that particular year. Since the MODIS LU/LC data are only available till 2013, the 2013 data are also used for the years 2014–2017. Unless otherwise stated, the daytime UHI is derived from the mean of LST values at 1030 and 1330