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Urban heat island effect: A systematic review of spatio-temporal factors, data, methods, and mitigation measures

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ABSTRACT

Despite research on urban heat island (UHI) effect has increased exponentially over the last few decades, a systematic review of factors contributing to UHI effect has scarcely been reported in the literature. This paper provides a systematic and overarching review of different spatial and temporal factors affecting the UHI effect. UHI is a phenomenon when urban areas experience a higher temperature than their surrounding non-urban areas and is considered as a critical factor contributing to global warming, heat related mortalities, and unpredictable climatic changes. Therefore, there is a pressing need to identify the spatio-temporal factors that contribute to (or mitigate) the UHI effect in order to develop a thorough understanding of their causal mechanism so that these are addressed through urban planning policies. This paper systematically identified 75 eligible studies on UHI effect and reviews the nature and type of satellite images used, the techniques applied to classify land cover/use changes, the models to assess the link between spatio-temporal factors and UHI effect, and the effects of these factors on UHI. The review results show that: a) 54% of the studies used Landsat TM images for modelling the UHI effect followed by Landsat ETM (34%), and MODIS (28%); b) land cover indices (46%), followed by supervised classification (17%) were the dominant methods to derive land cover/use changes associated with UHI effect; c) ordinary least square regression is the most commonly applied method (68%) to investigate the link between different spatio-temporal factors and the UHI effect followed by comparative analysis (33%); and d) the most common factors affecting the UHI effect as reported in the reviewed studies, include vegetation cover (44%), season (33%), built-up area (28%), day/night (25%), population density (14%), water body (12%) together with others. This research discusses the findings in policy terms and provides directions for future research.

1. Introduction

This paper reports a systematic and overarching review of the literature on urban heat island (UHI) effect. The main objective of this research is to review two broad categories of factors underpinning the UHI intensities: a) spatial factors – the impacts of changes in the spatial aspects of urban environment (e.g. changes in urban form and land cover patterns) on UHI intensity; and b) temporal factors, that is, how UHI intensities vary between different temporal scales such as yearly, seasonal, diurnal, and nocturnal. However, an overarching review, including data and methods applied to generate the two types of factors, is necessary in order to provide readers with sufficient background associated with the main objective of the paper. Current literature has already been enriched with a number of review articles on UHI effect as shown in Table 1. However, none of these reviews focuses on the factors contributing to the UHI effect, rather, the emphases of these studies are on satellite technology, methodology, modelling techniques, and mitigation measures of the UHI effect. A thorough understanding of the factors contributing to the UHI effect is important to devise appropriate policy mechanism and planning for cities to mitigate the UHI effect, and thereby, to avoid severe undesirable consequences for both human being and the environment.

Our preliminary analysis shows that the impact of different spatio-temporal factors on UHI effect varies between the type of satellite imagery used and the methodology applied to derive the UHI intensities. As a result, this research also reviewed the strengths and weaknesses of different data types and methodologies, with an aim to identify which type of datasets and methodologies provide more accurate results.

UHI is a phenomenon when urban areas experience higher temperature compared to their surrounding non-urban areas (Rizwan et al., 2008). The adverse effect of UHI has been widely documented in the

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Table 1
Past review studies of UHI.

Review Study	Focus of the review
Mohamed et al. (2017)	Review of the theoretical background of different measures used to estimate land surface temperature (LST) from the thermal infrared part of the electromagnetic spectrum.
Chapman et al. (2017)	Review of the impact of climate change and urban growth on future urban temperatures and the potential for increased heat stress on urban residents.
Rasul et al. (2017)	Review of urban heat and cool island studies occurred in dry climate.
Jamei et al. (2016)	Review of the pedestrian level urban greening and geometry to improve thermal comfort in cities.
Tzavali et al. (2015)	Review of the UHI intensity level by continents in the world.
Mirzaei (2015)	Review of the compatibility of various models used to predict and mitigate the UHI intensity.
Phelan et al. (2015)	Review of the mechanism, implications and possible remedies of the UHI effect.
Santamouris (2014)	Review of the technologies used to increase the albedo of cities (e.g. green roof) to mitigate the UHI effect.
Gago et al. (2013)	Review of different policy strategies that can be applied to mitigate the UHI effect.
Block et al. (2012)	Quantification of the cooling and energy-saving benefits of three types of green infrastructure: shade trees; green roofs; and vertical greening.
Tomlinson et al. (2011)	Review of different satellites and their sensors for capturing the electromagnetic radiation used to derive LST in the context of meteorology and climatology.
Mirzaei and Haghighat (2010)	Review of the approaches (e.g. modelling, prediction and mitigation) used to study UHI.
Weng (2009)	Review of existing practices (methods, techniques, applications) as used in the UHI studies together with their problems, and prospects.
Rizwan et al. (2008)	A review on the generation, determination and mitigation of urban heat island.
Stefanov and Brazel (2007)	Review of the different temporal and spatial scales used in climatology and the basic factors that influence urban climate and how remote sensing technique is contributing to this area of study.
Stathopoulou and Cartalis (2007b)	Review of the potential of satellite remote sensing for the study of urban climatology with special reference to surface UHI effect.
Weng and Larson (2005b)	Review of the practices of satellite remote sensing techniques used in UHI studies.
Voogt and Oke (2003)	Review of the application of thermal remote sensing with particular emphasis on the UHI effect.

literature. For example, it increases temperature of cities; contributes to global warming (EPA, 2016); initiates storms/precipitation events (Bornstein and Lin, 2000; Dixon and Mote, 2003); increases energy demand of cities (Santamouris et al., 2015); and contributes to heat-related mortality (Hondula et al., 2014). These devastating effects necessitate devising ways to mitigate the UHI effects (Chow et al., 2012; Gago et al., 2013; Susca et al., 2011). As a result, it is critical to know what factors cause the UHI effect so that these factors can be targeted to lessen the effect through appropriate policy interventions.

Studies have derived the UHI effect in three ways depending on their measurement altitudes: boundary UHI, canopy UHI, and surface UHI (Zhang et al., 2009). Boundary UHI is measured from the altitude of rooftop to the atmosphere (Mirzaei and Haghighat, 2010). It is generally used to investigate the UHI effect at mesoscale (i.e. 1–10,000 km^2) and is derived using, for example, radiosondes (Voogt, 2007). Canopy UHI is measured at the altitude that ranges from the ground surface to the rooftop (Voogt, 2007). An assessment of canopy UHI is most suitable for a microscale study and is generally derived based on weather station data (Kato and Yamaguchi, 2007). Surface/skin UHI (SUHI) is measured at the earth surface level. Researchers often used satellite images (e.g. thermal bands of Landsat TM/ETM/OLI) to derive the surface UHI effect. It is measured by calculating the difference of land surface temperature (LST) between urban/built-up and non-urban areas (e.g. waterbody and vegetation areas). NASA (2017a) defined LST as "how hot the surface of the Earth would feel to the touch in a particular location". Further information about LST is available on (Li et al., 2013; Li and Duan, 2017). The scope of this study is limited to surface urban heat island which hereafter refers to as UHI in this paper. The paper also includes review of prior studies that termed LST effect as UHI effect.

The paper is structured in four sections. After this introduction, the following section explains the approaches used to select literature suitable for the review. The identified publications are reviewed under four headings: 1) characteristics of the satellites and acquired images that were used for the derivation of UHI effect; 2) methods employed to measure spatial changes such as urban growth and land cover changes; 3) analytical methods used to establish an association between different spatio-temporal factors and UHI/LST intensities; and 4) the impacts of different spatio-temporal factors on UHI effect. Subsequently, a broad overview of policy implications of the reviewed studies for mitigating UHI intensity is presented. The last section provides conclusions and ways to move forward for future research.

2. Methodology – criteria used to select literature on UHI effect

This research applied a standard approach for the systematic review of the literature on a particular topic of interest (UHI in this case) and consists of four stages (Pullin and Stewart, 2006; Stewart, 2011): (1) identification of a broad search criteria to obtain the population/universe of studies; (2) limiting the universe of studies to targeted/eligible literature using rigorous and clear criteria; (3) deriving information from eligible documents and coding them into informative statistical values; and (4) presenting a discussion about findings of selected studies. This study used Internet search technique to find relevant literature. The search was conducted within 393 dominant databases of academic literature using the library portal of a university. Examples of such databases include Scopus, Web of Science, Wiley online library, directory of open access journals (DOAJ) and ScienceDirect.

In this study, a hurdle was to reach an efficient search strategy to find suitable articles, as various terminologies have synonymously been used to refer to a particular topic in the literature. Therefore, two combinations of terminologies were used to collect the universe of literature as outlined in Table 2, which resulted in 400 publications. These were then screened by reading the publication title and abstract to identify eligible studies for review. The screening resulted in 100 publications for detailed eligibility check. The detailed check was conducted to examine whether the publications meet the following three criteria, that the publication: (1) used satellite images to derive surface UHI; (2) investigated the influence of either spatial or temporal factors on UHI intensities; and (3) applied statistical models/techniques

Table 2
Criteria used to select publications for review in this research.

Key words within abstract	"urban heat island" AND "satellite image" AND "spatio-temporal" "land cover change" OR "land use change" AND " urban heat island" AND " satellite image"
Document Type	Journal articles, conference proceedings, book chapters
Peer-review status	Only peer-reviewed documents
Language	English
Publication date range	January 1965–30 July 2017