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Review

A Review on Remote Sensing of Urban Heat and Cool Islands

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Academic Editors: Andrew Millington, Harini Nagendra and Monika Kopecka
Received: 20 April 2017; Accepted: 6 June 2017; Published: 9 June 2017

Abstract: The variation between land surface temperature (LST) within a city and its surrounding area is a result of variations in surface cover, thermal capacity and three-dimensional geometry. The objective of this research is to review the state of knowledge and current research to quantify surface urban heat islands (SUHI) and surface urban cool islands (SUCI). In order to identify open issues and gaps remaining in this field, we review research on SUHI/SUCI, the models for simulating UHIs/UCIs and techniques used in this field were appraised. The appraisal has revealed some great progress made in surface UHI mapping of cities located in humid and vegetated (temperate) regions, whilst few studies have investigated the spatiotemporal variation of surface SUHI/SUCI and the effect of land use/land cover (LULC) change on LST in arid and semi-arid climates. While some progress has been made, models for simulating UHI/UCI have been advancing only slowly. We conclude and suggest that SUHI/SUCI in arid and semi-arid areas requires more in-depth study.

Keywords: land surface temperature (LST); urban climate; surface urban cool island (SUCI); remote sensing; review

1. Introduction

Surface urban heat islands (SUHI) are one of the crucial topics in urban climatology studies. The comfort of the urban inhabitants is influenced by surface temperature through modified air temperature of the lowest layer of the urban atmosphere [1]. The land surface is a complex feature that can be described as a combination of green vegetation, water surfaces, impervious surface materials and exposed soils. As a result of this complexity, LST varies spatially and temporally. Impervious surface differs considerably between urban and suburban areas and it is the main contributor to the SUHI effect [2–4]. The results by Rasul et al. [5,6] from Landsat and MODIS LST indicate the existence of SUCI in semi-arid cities during different times of the day and not only in the morning as stated in other literature [7–10].

Since the early 1900s, the UHI intensity of hundreds of urban areas around the world have been assessed [11] and this field remains an extensive area of study within urban climatology [12]. The growth and strength of the heat island areas during this time bring challenges for energy, the health of urban residents, water supplies, urban infrastructure and social comfort [13]. In addition, it exacerbates heat waves and creates a negative effect on life expectancy on urban inhabitants [14].

Ignoring atmospheric correction means assuming that atmospheric effects are the same in all places, while in reality, water vapor and pollutant contents vary horizontally in urban areas. If the atmospheric correction is neglected or is incorrectly, estimated surface temperature SUHI intensity may be incorrectly derived [15,16]. Typically, the average surface emissivity in urban areas is about 2% lower than the typical rural areas [17]. Without emissivity correction and neglecting this difference, temperature retrievals of urban-rural environments can show differences of 1.5 °C or more. Therefore, the urban heat island effect can typically be underestimated [15].

Reviews of the retrieval of LST, SUHI, generating, determination and mitigation UHI was carried out by a number of authors [18–20]. However, a review of the SUHI/SUCI in dry climate and methods used for studying the SUHI is still lacking.

The objective of this paper is to review the state of knowledge and current research to quantify the SUHI/SUCI. This paper provided knowledge on the techniques used for SUHI and SUHI/SUCI that were based on different climatic regions, specifically for the arid and semi-arid climates.

The articles reviewed in this paper are based on techniques and methods. Moreover, sampling of research for different remote sensing data and SUHI/SUCI from different climatic regions was reviewed. There extensive research on UHI in humid regions, thus this paper focused on SUHI/SUCI in dry climate.

2. Techniques and Statistics Used in Urban Heat Island Studies

2.1. Methods to Compare Multi-Temporal LST Images

In the literature, various techniques have been applied for analyzing the temporal change of satellite based LST. In the first technique, some researchers directly compare two or more LST images without any modification [21]. This approach lacks scientific rigor because the atmospheric situation is not the same at the time of image acquisition. Having a high temperature in the second image compared to the first one, for example, does not mean the temperature has increased because it is possible that at that time the temperature was high for other reasons. The second technique to account for this and to better establish the SUHI is through the normalization of the temperature based on the mean and standard deviation in high and low temperature areas [22,23]. The third technique is common normalization of temperature based on min and max LST of the same image in the same way as for NDVI [24]. A Normalized Ratio Scale (NRS) technique is proposed by Rasul et al. [25], to normalize the value of each pixel-based ratio to make the LST images from different times comparable and at the same time maintaining the original values.

2.2. Determining the Urban Heat Island

Researchers used various methods to assess UHI; for instance, Tran et al. [26] have used satellite data to assess maximum SUHI. Hafner and Kidder [27] have used a model to assess SUHI. UHI was determined in some studies as a comparison of the mean and maximum temperature between urban and rural areas. Others compared temperature during times such as a season, a month, a year or some days. In some cases, it was selected as temperature changes over time [28]. Moreover, Magee et al. [29] selected UHI as the average changed temperature for both the urban and the rural areas [20].

For determination of SUHI, the comparison of mean urban and rural patterns provides robust results. The use of trends of LST before and after urbanized areas illustrated the significant influence of urbanization on the UHI but many cities have no historic records of LST before urbanization which creates an obstacle for SUHI studies.

2.3. Statistical Analyses of Urban Heat Islands

Weng et al. [30] conducted pixel-by-pixel correlation analysis between surface temperature on the one hand, and NDVI, green vegetation (GV), and impervious surface fractions on the other hand.

Linear regression has been used extensively in UHI studies to show the relationship between LST and NDVI [31–33]. Szymanowski and Kryza [34] conducted Multiple Linear Regression (MLR) to state the land-use situation of the UHI, but inaccurate results have been obtained when the process tended towards non-stationary variables such as the impact of the wind. The common character of meteorological data is non-stationary, hence the application algorithm can be largely limited in case the technique is unable to manipulate it. According to Szymanowski and Kryza [34] and Su et al. [35], geographically weighted regression (GWR) is better suited than MLR and other conventional regression analyses. GWR shows the relationship between temperature and land covers more clearly and it is more successful in the spatial modelling of UHI.

For spatial modelling of the UHI, Szymanowski and Kryza [34] suggested the combined GWR residual kriging (GWRK) method as an alternative to the extensively used MLR model. Florio et al. [36] emphasized that the kriging models estimates temperature better than MLR. RK errors are neutral while regression models are inclined to give biased predicted values. RK and GWR methods have been also been applied to LST [37,38].

3. Surface Urban Heat Island

Surface urban heat island intensity (SUHII) is determined by variations of surface temperature between urban and surrounding rural areas with similar geographic characteristics. Remote sensing sensors, thermal images and field data have all been used to assess the SUHII of urban areas.

3.1. Satellite Measurements of Urban Heat Island

In order to ascertain surface temperature through radiation the traditional technique of aerial surveillance is commonly used [39–41]. Thereafter, Wark et al. [42] and Rao and Winston [43] attempted to utilize satellites to measure surface temperatures. Through data obtained from the Television Infrared Observation Satellite (TIROS II), they found that measuring surface temperature is possible in clear and dry areas [44]. Primarily, LST and SUHI have been derived from the National Oceanic and Atmospheric Administration's (NOAA) AVHRR data [30]. After that, Landsat's Thematic Mapper (TM) and Landsat's Enhanced Thematic Mapper Plus (ETM+) were widely employed to retrieve surface temperatures [30,45,46]. Srivastava et al. [47] estimated surface temperature in the Singhbhum Shear Zone of India. The results indicated that emissivity has a strong relationship with the reflectance of ETM+ band 3. They compared field data with estimated LST from different algorithms. It was found that the use of Valor's emissivity and single channel equations increase the accuracy of the result and is closer to field truth temperature.

Surface UHI can be derived from remote sensing images as a captivating and possibly valuable source [2,15]. Rao [48] reported the first study of SUHI based on imagery data. Through the study of surface temperature patterns of the mid-Atlantic coast of USA, the study utilized thermal Infrared Radiometer (IR) data of the Improved TIROS Operational Satellite (ITOS-1). The research found that the center of the city is the warmest part. Matson et al. [49] and Price [50] detected the UHI by utilizing satellite data. Since then, the SUHI and surface temperature have been observed through utilizing different sensors such as satellites, aircrafts, and ground-based sensors. Later, in 1989, Roth et al. [19] studied the thermal urban climates.

The AVHRR sensor has been used to discern the surface temperature [51–53] and to analyze the regional-scale of UHI effects [22,54,55]. Airborne acquired high-resolution images were also used to assess the thermal determiners of urban surfaces such as sky view factor and surface materials [19]. The ASTER is another sensor of the TIR image that collects both daytime and night-time data and has been used for determining the UHI effect in many cities [56–58].

Landsat images are widely used to investigate the growth of SUHIs and to assess the relationship between LST and land use/land cover (LULC) [59–61]. Unfortunately, calibration problems with Landsat 8 TIRS have restricted its use. Clinton and Gong [62] used MODIS at 1 km special resolution with high temporal resolution to investigate UHIs and Urban Heat Sinks (UHSs) of cities on a global scale. Furthermore, MODIS data has been used to analyze daily differences of LST and UHI in Abu Dhabi. Standard nocturnal UHIs were found in the city, while during the day the city center was cooler than its surroundings [63].

The selection of LST data for SUHI studies varies based on the purpose of the research and the availability of remotely sensed data. Landsat images (with 30 m spatial resolution) are appropriate for investigating the spatial variation of SUCI/SUHI and the effect of LULC change from different samples of classes on LST, whereas MODIS LST (with higher temporal resolution) is effective for studying the temporal variation of SUHI/SUHI (e.g., diurnal, seasonal and decadal) at coarser scales. ASTER LST with high spatial resolution is appropriate for quantifying the variation of SUHI between day and night. In general, aircraft-based LST data have higher resolution, but it is expensive and the areal coverage is irregular and it is a non-standardized product while satellite-based LST has extensive spatial coverage, limited spatiotemporal resolution and is influenced by atmospheric effects on the signal [64].

The result of comparison LST of the urban and rural surroundings may vary based on day/night, location and different climatic patterns of the cities (Table 1). The table illustrates the highest SUHI exists in cities with the "Dwa" and "Csb" Köppen climate types while the highest SUCI is found in cities located in "Bwh" and "BSh" climates.

Table 1. A summary of surface UHII/UCII in different areas of the world.

Type	Study Area	Climate	Reference Study	Approach	UHII/UCII °C
Daytime SUHI	Beijing, China	Dwa: Hot Summer Continental	Tran et al. [26]	Satellite data	10
	Vancouver, Canada	Csb: Warm-summer Mediterranean	Roth et al. [15]	Satellite data	7.5
	Medellin, Colombia	Af: Tropical Rainforest	Peng et al. [65]	Satellite data	7
	Athens, Greece	Csa: Dry-summer Subtropical	Stathopoulou and Cartalis [66]	Satellite data	3.3
Nighttime SUHI	Madrid, Spain	Csa: Dry-summer Subtropical	Sobrino et al. [67]	Airborne	5
	Birmingham, UK	Cfb: Marine West Coast	Tomlinson et al. [68]	Satellite data	5
	Erbil, Iraq	BSh: Subtropical Semiarid (Hot Steppe)	Rasul et al. [6]	Satellite data	4.59
	Manila, Philippines	Aw: Tropical Savanna	Tiangco et al. [57]	Satellite data	2.96
	Atlanta, USA	Cfa: Humid Subtropical	Hafner and Kidder [27]	Modeling	1.2
Daytime SUCI	Abu Dhabi, UAE	Bwh: Subtropical Desert	Lazzarini et al. [63]	Satellite data	−6
	Dubai, UAE	Bwh: Subtropical Desert	Frey et al. [69]	Satellite data	−5
	Erbil, Iraq	BSh: Subtropical Semiarid (Hot Steppe)	Rasul et al. [5]	Satellite data	−3.9
	Cairo, Egypt	Bwh: Subtropical Desert	Shahraiyni et al. [70]	Satellite data	−3.1
	Central India	Cfa: Humid subtropical and (Aw) tropical wet and dry	Shastri et al. [71]	Satellite data	−2.5

3.2. Urban Heat Island in Arid and Semi-Arid Climate

SUHI studies pay more attention to urban areas located in tropical, Mediterranean and cold climatic regions whereas arid regions with extreme high temperatures have been less focused on [72]. Moreover, the effect of LULC change on LST has been widely assessed for cities in the humid climate while in cities located in semi-arid environments requires more focus to be better quantified and understood. Some of the few UHI studies in the literature based in arid regions were carried out in Phoenix and Tucson, Arizona by Tarleton and Katz [73], Kuwait City by Nasrallah et al. [74], Erbil City by Rasul et al. [6] and the Al Ahsa oasis by Al-Ali [72]. The effect of land cover on UHII of the Al Ahsa oasis in Saudi Arabia has been assessed by using both ground data and satellite images. The limitation of approach in such research is in comparing urban area with nearby towns to study UHI and ignoring the bare soil and desert sand surrounding the city that has high LST in arid and semi-arid regions. In semi-arid regions, the importance of changing aridity soil moisture in the rural areas in modifying heat islands has not been studied extensively.

4. Urban Cool Islands

The general conviction that the air temperature in green sites can be cooler than non-green sites was confirmed by many studies on the temperature of parks and forest cover [75]. To explain the effect of parks on the temperature of cities in detail, more research is necessary on the design of urban green area, distribution and type of greening. Studies on many parks indicated that the temperature is cooler in larger parks and those with trees [75]. On average, larger parks are cooler than smaller ones but not always, while the urban cool islands (UCI) of the parks is more related to the characteristics of the parks [76]. The results from the study indicate that 61 parks in Taipei city were confirmed as UCIs whereas around one-fifth of parks with ≥50% paved coverage and little tree and shrub cover, have been warmer than their urban surrounding at midday during the summertime [77]. Several studies have confirmed that this so-called "oasis" exhibits the cold island effect [78,79]. In some environments such as arid, semi-arid, arctic and subarctic, cities have been reported as UCIs (negative UHI) during certain times of the day or during particular seasons [27,80,81].

During the dry season the daytime SUHI intensity in some cities such as Mexico City and Reykjavik is very weak and sometimes exhibits a cold island. As a result of high thermal inertia, urban places in arid areas have the capability of showing both nocturnal SUHIs and diurnal SUCIs [62]. The amount of soil moisture and humidity in urban areas have an effect because evaporation via latent heat reduces LST. As such, the investigation proved the existence of UCIs in Dubai compared to the desert areas [77,82,83].

To date, plenty of research has investigated SUHI and SUCI in green spaces and water bodies within cities whereas only a few studies have investigated Surface Urban Cool Island across a whole urban area so it is requiring greater comprehension. Usually, research of atmospheric UHI uses measured air temperature of some points in and around the city that not represent the study area entirely. However, because SUHI studies usually use remote sensing data it represents the temperature of the whole of the study area with some consistency.

5. Future Research Directions

There is a need to utilize remote sensing data in investigating surface temperatures of cities in dry and semi-dry environments on a large scale. That study is a necessary requirement in the description of surface characteristics in this specific environmental climate class. Furthermore, since urban climate archipelagos produces an aggregate impact on temperature, moisture or precipitation [84], future studies should focus on SUHI archipelagos.

Even higher spatial resolution with more temporal sampling and improved better calibrated data would be very useful. The application of higher resolution remote sensing data facilitates study on UHI characteristics and urban climate. Moreover, a future sensor improving on Landsat and aircraft thermal data are some possible options. On the other hand, in order to determine a temporal variation of LST using satellite data at restricted overpass times, it appears necessary to use field data to investigate diurnal UHI in dry environments. Future research should improve methods to simultaneously derive LST and LSE from hyperspectral TIR, multi spectral-temporal, TIR-microwave data, and methods should consider aerosol and cirrus effects [18].

In addition, another viable angle of future studies should focus on mitigation strategies for night-time SUHI and explore surface materials that can reduce surface temperature in urbanised areas in dry regions. Research should look more closely at different parts of the city. Finally, the area needs the development of more research on techniques to reduce LST in rural areas surrounding the cities in dry regions such as the effect of irrigated vegetation in the dry season and increased soil moisture through artificial streams.

Acknowledgments: The authors would like to thank the HCDP Scholarship Programme and Soran University for their financial support of this research. H. Balzter was supported by the Royal Society Wolfson Research Merit Award, 2011/R3 and the NERC National Centre for Earth Observation.

Author Contributions: Azad Rasul conceived the review research. Azad Rasul, Heiko Balzter and Claire Smith all contributed in designing the review, writing and editing it. All other authors contributed in evaluating, improving and editing the paper. The list of authors from the fifth author to the end ordered alphabetically.

Conflicts of Interest: The authors declare no conflict of interest.

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