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Assessment of Urban Heat Island in India using Geospatial Technology- A Review

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Abstract

The higher temperature of urban areas than surrounding regions is manifestation of widening urban-rural contrast under the influence of several anthropogenic activities such as change in land use- land cover, ongoing urbanization etc. The occurrence of UHI effect is one such thermal outcome of urban-rural contrast that reflects higher warming of an urban area than its nearby sub-urban and rural regions. Here, a brief review regarding the history of research carried out on the estimation of UHI in India induced by urbanization and several other factors has been presented. The geospatial technology used for estimation and mapping of urban heat island effect has also been discussed as the advancements in thermal remote sensing with improved spatial and spectral resolution for qualitative and quantitative estimation of urban and rural surfaces have provided new insights in urban climatic studies. Moreover, numerous consequences of the UHI effect on environment and human health are summarized. Finally, the potential mitigation strategies to control the UHI effect have also been suggested in this review.

Introduction

Inadvertently varying climatic trends are alarming condition throughout the world. These climatic variations such as imbalance in the hydrological cycle, energy flow and thermal imbalance etc owe to the numerous ongoing activities occurring in our day-to-day life. Alteration in the type of land use/land cover (LULC) due to rapid urbanization is one of such anthropogenic activities that significantly imply climate change from local to regional scales (Kikon *et al*., 2016). The swift urbanization and increasing global temperature are stimulating the urgency to comprehend urban areas and their climatic implications. Hence, to analyze the role of urban areas in climate change, 'Urban Heat Island' (UHI) is one such example for better understanding of these climatic modifications in terms of temperature. Therefore, present study outlines the research carried with an objective to determine the occurrence of UHI in urban clusters and its effects.

Background of UHI

Urban heat island as first stated by 'Luke Howard' in 1833, is the phenomenon of higher temperature of the urban canopy as compared to surrounding rural areas that cools down more rapidly (Howard, 1833; Oke, 1982; Voogt and Oke, 2003). The exacerbating urbanization is the chief factor for the occurrence of urban heat island which is a matter of global concern. Being prominent outcome of rising urban sprawl, this phenomenon warms up entire urban area. Rising level of global warming will readily affect cities that are already facing UHI effect (Tan *et al*., 2010).

The concept behind the formation of UHI can be described as the temperature disparity in urban and nearby rural areas. The temperature differentiation occurs due to increase in sensible heat and decrease in latent heat flux in urban areas; as most of the urban areas are developed by the switchover of vegetated surfaces to the constructed surfaces with different thermal characteristics (Oke, 1982; Gallo *et al*., 1993). The thermal and radiative properties of these urban fabrics depend on the type of building materials, geometry and type of LULC (vegetation, barren land, water bodies). Urban clusters with impervious surfaces exhibit greater absorption of solar radiations insolated on them than the surrounding rural regions. So, the absorbed radiations consequently elevate the temperature of urban sprawls of higher thermal capacity surfaces that give rise to the formation of UHI (Imhoff *et al*., 2010).

Causes of UHI formation

The urban heat island phenomenon is a consequence of many factors; the most important of which are summarized as follows:

Temperature is one of the chief parameters in urban climatic studies. UHI being the most common phenomenon of climatic alterations is temperature driven (Voogt and Oke, 2003; Liu and Zhang, 2011). Higher urban and simultaneous lower rural temperature implies higher magnitude of UHI effect. Skin temperature of the land surface that represents the surface temperature for barren land, canopy surface temperature for vegetated surfaces is outlined as land surface temperature (LST); that induces surface UHI phenomenon (defined later). LST is acquired from satellite data with the wavelength range in thermal infrared region (TIR) i.e., 8–15 µm, to estimate and map LST trends for UHI analysis for various regions (Yuan and Bauer, 2007). LST is retrieved from TIR

(Thermal Infrared) band by conversion of digital numbers to spectral radiance or radiant temperature (Kikon *et al*., 2016).

Land use/Land cover (LULC) variations: LULC is another significant factor in UHI assessment. The variations in LULC influence intensity and occurrence of UHI effect (Chen *et al*. 2006) and therefore, numerous studies have been conducted in the context of LULC changes describing the influence of variability in land use types on urban temperature and hence UHI effect (Hawkins *et al*., 2004; Jiang and Tian, 2010; Busato *et al*., 2014). The quantitative and qualitative estimation has been widely done for determining the correlation between UHI and LULC. Multi-temporal satellite images are commonly used for consideration of trend of LULC changes (Mondal *et al*., 2015). These land use land cover changes that influence UHI effect include loss of forest and agricultural lands, increase in barren area and impermeable surface area etc.; some of which are discussed below:

Urbanization: UHI formation is considered as the foremost implication of urbanization. The rapidly growing urban population has induced LULC variations by ramifying agricultural and open areas into dense and large built-up infrastructure (Chadchan and Shankar, 2012; Jiang *et al*., 2013). These built-up areas of urban regions trap and absorb more solar insolation during daytime due to certain building characteristics thereby increasing urban temperature than surrounding cool rural areas. The rural areas have been converted into suburban, suburban into urban and urban areas have turned into megacities under the swift urbanization process, thereby aggravating the UHI effect. The effect of urbanization on minimum and the average temperature is certainly more pronounced than on maximum temperature because the low urban temperature varies with the nighttime heat emissions from buildings and paved surfaces (Oke, 1982; Kalnay and Cai, 2003). Numerous studies have been carried out to monitor the role of urbanization in increasing local atmospheric temperature (Weng and Yang, 2004; Singh *et al*., 2017). Besides the prevalent occurrence of UHI effect in highly urbanized clusters, the occurrence of UHI has been reported for even small populated (< 10,000) urban regions (Karl *et al*., 1988).

Urban characteristics

Vegetation and water bodies**:** Vegetation cover is one of the chief components to understand UHI effect as rural areas with the large surface under vegetation have low thermal capacity than the urban built-up surfaces (Carlson *et al*., 1981). Furthermore, vegetation uses substantial amount of solar flux for photosynthesis and thus holds considerable proportion of solar radiation that instead is diffused to the atmosphere which causes additional heating of region. The decrease in area under vegetation and water bodies results in lowering of evapo-transpiration, decreased soil moisture that lowers cooling of urban areas (Oke, 1981). So, the extent and amount of vegetation and water bodies present in urban area affects LST of that area and thus influences the spatiotemporal variations in UHI trends (Ramachandra *et al*., 2015). NDVI (Normalized

Difference Vegetation Index) is an index used to quantify and determine the variations in vegetated areas with the use of satellite data while NDWI (Normalized Difference Water Index) is used for estimation of water content (Chen *et al*., 2006). Urban areas with reduced vegetation generally exhibit lower NDVI and thus high temperature. The negative correlation found between LST and NDVI is of great importance for climate-related studies (Yuan and Bauer, 2007).

***Urban buildings and geometry*:** The dense built-up area of cities comparative to surrounding rural areas with sparse building density induces UHI effect (Mallick, 2014). The introduction of highly dense infrastructure in urban clusters at the expense of vegetation increases absorption of sunlight at daytime, reduces sky-view factor and retards cooling by the long-wave radiative loss at night. Thus, the urban parameters such as building density, sky view factor share a strong relationship with the UHI effect (Bottyan and Unger, 2003). Furthermore, the roughness of urban infrastructure attenuates wind speed comparative to nearby open vegetated areas and thus lessens heat removal by convection (Rizwan *et al*., 2008). The giant buildings with less albedo influence the heat storage within the urban areas. This urban-rural contrast is the base for the elevated temperature in urban areas that results into UHI formation. The warm urban regions exhibit UHI of magnitude 3–5°C during the daytime that intensifies to 12°C during nighttime because of complex urban geometry (Oke, 1967; Kikon *et al*., 2016). NDBI (Normalized Difference Built-up Index) is commonly used to determine urban and built-up areas using geospatial technology (Zha *et al*., 2003).

***Surface characteristics*:** The artificial built-up urban surfaces made by replacing vegetated surfaces have high heat capacity, thermal admittance etc that enhances absorption and heat storage in urban areas (Akbari *et al*., 2001). These impervious surfaces such as asphalt, concrete, bricks etc, subsequently multiplies the urban temperature. The larger urban surface area covered by these non-evaporating surfaces consequently increases the sensible heat flux that cause the formation of UHI (Oke, 1982; Owen *et al*., 1998). The area under impervious surfaces is related to the extent of urbanization and its population and is mapped by using remote sensing techniques as percent impervious surface area (%ISA) (Yuan and Bauer, 2007). The percent impervious surface area estimation is considered more stable over NDVI. This is because impervious surface area calculation is less prone to seasonal changes than NDVI and is a useful parameter for estimation of thermal properties of urban surfaces. Moreover, the strong relationship between LST and %ISA determined using satellite data assures it as an indicator of the UHI phenomenon (Yuan and Bauer, 2007).

***Albedo*:** Most of the urban surfaces are dark in color with low albedo values. These low albedo urban surfaces cause absorption of short-wave radiation from the solar insolation and trap the radiations as multiple reflections takes place between the buildings and street surface. This ultimately causes increase in urban temperature. While rural surfaces with higher vegetation cover have high albedo values, which reflect sunlight resulting in low temperature. Therefore, the temperature disparity induced by low albedo of urban regions than surrounding rural regions implies UHI effect. A negative correlation between albedo and LST has been observed for numerous urban sites (Kikon *et al*., 2016).

Meteorological conditions: Meteorological conditions of an area are another important parameter in UHI formation. Meso- and synoptic scale circulations affect the intensity of this phenomenon (Gedzelman *et al*., 2003; Kim and Baik, 2004). Additional heating of urban buildings occurs with the high amount of solar radiations received in the clear atmospheric conditions. Therefore, the intensity of the UHI effect is generally high during calm wind (0 to 2 m/s) and clear atmospheric conditions (Memon *et al*., 2010). The amount of solar insolation decreases with the clouds and increased wind speeds that lower the urban air temperature (Grimmond, 2007). Hence, a considerable lessening of urban-rural temperature difference can be observed with increase in wind speed and cloud cover as UHI is nearly the fourth root of these factors (Oke, 1982; Morris *et al*., 2001; Kim and Baik, 2005). Attenuation in UHI intensity is remarked at a higher wind speed of 7.0-8.0 m/sec while it may destroy at very high wind speed due to the turbulent mixing of air caused by these high-speed winds (Kim and Baik, 2002; Alonso *et al*., 2007). So, a limiting or threshold wind speed was defined above which UHI effect nullifies (Oke, 1976). Frequently occurring nighttime UHI effect could be reduced due to the cloudy atmosphere that elevates emissivity of the atmosphere (Arnfield, 1990; Oke *et al*., 1991). So, a negative correlation was seen among cloud cover and nocturnal UHI effect (Kim and Baik, 2004).

Geographic location/ topography: Besides, other factors, the topography of the site also plays a significant role in UHI formation. The daily mean UHI was recorded smaller for coastal urban areas compared to inland urban regions (Kim and Baik, 2004).

Urban activities: The UHI phenomenon is further intensified by the heat emissions from the burning of fuel, air conditioners, industries, vehicular traffic and residential buildings in urban areas (Taha, 1997; Sailor, 2011).

UHI measurement

UHI being most documented temperature effect of urban areas is estimated by numerous ways of which comparison of urban air temperatures with non-urban (rural, suburban) temperatures is eminently carried out (Oke, 1987). Existing literature shows that the climate modifying phenomenon of UHI can be investigated with the use of air temperature assessed from ground or field based measurements and land surface temperature acquired with remote sensing satellites. The air temperature accessible from meteorological stations gives the temperature values of urban air lying between lower atmospheric layer and height of the buildings in urban clusters (Arnfield, 2003; Stewart, 2011; Schwarz *et al*., 2011). Thus, the urban canopy layer studies are monitored with the air temperature variations while surface temperature acquired with satellite sensors depicts surface urban heat island (SUHI) (Voogt and Oke, 2003). UHI estimation can be done by recording maximum temperature difference between urban-rural areas or by average temperature difference between them. Besides, monthly, seasonal and annual temperature monitoring can be done for respective UHI study (Rasul *et al*., 2017).

Types of UHI

Based on the method and duration of measurement, certain terminologies are used for UHI phenomenon such as:

Atmospheric UHI: Atmospheric UHIs are estimated by measuring air temperature of urban and surrounding rural areas. These can further be categorized as Canopy and Boundary layer UHI. Canopy layer UHI is estimated from ground surface extending to average building height whereas Boundary layer UHI is determined for air beyond canopy layer. The phenomenon of atmospheric UHIs is mainly observed during nighttime (Roth *et al*., 1989; Yuan and Bauer, 2007; Sharma and Joshi; 2014).

Surface UHI: It is a surface temperature based effect. The measurement of surface UHIs is mostly done by estimating LST using satellite data. Surface UHIs are mostly prevalent during daytime (Roth *et al*., 1989).

Diurnal UHI: The daily variations in urban-rural temperature are stated as diurnal UHI effect. This can be for daytime temperature difference or for nighttime, also called nocturnal UHI.

Seasonal UHI: The variations in UHI effect differs according to the season for different climates. The classification of UHI effect in temperate climates is based on summer and winter months while it is dry or wet season based categorization for tropical climates (Arnfield, 2003; Jonsson, 2004).

Effects of UHI

The consequences associated with UHI phenomenon varies according to the climatic conditions of a region. This can be stated as favorable UHI effects can be noticed in cold zones by urban warming that causes less building heating requirement and hence the reduced energy consumption. But in contrast to this, negative effects of UHI are experienced in hot urban areas facing warming, as the cooling requirement increases energy consumption there (Roth and Chow, 2012). Besides, the remarkable UHI effect confronted by most of the cities worldwide not only influences climatic imbalance, degrades water quality (Phelan *et al*., 2015) and elevates energy consumption but also give rise to numerous human health problems by intensifying air pollution (Sailor and Fan, 2002; Huang *et al*., 2011). So, the UHI effects can be categorized as follows:

Environmental impacts: The environmental impacts of UHI effect include deterioration of living environment by thermal and air pollution (Papanastasiou and Kittas, 2012) and rise in urban smog formation events with increased ground-level ozone (Rosenfeld *et al*., 1998; Sham *et al*., 2012). Urban warming induced from UHI effect also deteriorates the quality of environment as described below.

Urban warming**:** The increase in urban temperature leading to thermal discomfort is the consequential effect of the UHI phenomenon. The rise of approximately 1-3°C was reported in Vienna (Bohm, 1998); Los Angeles (Akbari *et al*., 2001) and Arizona (Baker *et al*., 2002) in the average annual temperature of the highly urbanized area has been observed compared to the nearby regions. This rise in temperature can maximize up to 12°C during the still and clear night time (Oke, 1982). In Indian context; the rise of 2-3°C temperature has been noticed in large Indian cities in short time span of 15 years (TERI) such as, shift in temperature from 1°C to 4°C for Pune city has been reported during 1999 to 2006 (Nesarikar-Patki and Raykar-Alange, 2012) while Dehradun i.e., another Indian megacity experienced 0.28°C per decade temperature rise (Singh *et al*., 2013).

Intra-urban temperature variations**:** The temperature disparity occurs not only between urban and rural areas, even the significant diurnal temperature variations are distinguished within the urban areas commonly described as intra-urban temperature difference (Svensson and Eliasson, 2002; Huang *et al*., 2011). Low speed of wind during clear skies favors intra-urban temperature variability (Grimmond, 2007). Numerous studies determined this temperature variability such as intra-urban air temperature difference of 2–8°C has been observed (Akbari *et al*., 2001; Svensson and Eliasson, 2002). Temperature variations of 1 to 7°C were witnessed within the urban area of Banglore, India due to the difference in land use (Ambinakudige, 2011). Urban geometry was stated as a causative factor for intra-urban temperature variations in a study of UHI effect for Gothenburg city of Sweden (Thorsson *et al*., 2011). A reciprocal relation was determined between SVF and intra-urban temperature (Chen *et al*., 2012). These temperature fluctuations have a considerable impact on energy requirements as human thermal comfort is associated with air temperature (Santamouris *et al*., 2001; Hondula and Barnett, 2014). Intra-city temperature variations were recorded higher for hot climates conditions than cold climates (Emmanuel, 1977).

Precipitation: The modified climatic conditions due to UHI have also altered the precipitation pattern. Restraining effect of UHI on precipitation has been found in various urban areas (Kaufmann *et al*., 2007). The reduction in rainfall in urban clusters is due to higher impervious surfaces in place of vegetation. The increased infrastructure reduces surface moisture and evapotranspiration. Also, the urban sprawl deepens the atmospheric boundary layer (Yan *et al*., 2016). However, increase in precipitation due to surface roughness has been noticed for various urban regions. Examination by high-resolution regional climate modeling recommends that precipitation effect may depend on rapidly growing urbanization as found in a study in North China. An increase in precipitation in downwind urban areas has been observed from previous research (Thielen *et al*., 2000; Burian and Shepherd, 2005); while some studies have mentioned the initiating effect of UHI on precipitation (Baik *et al*., 2001; Rozoff *et al*., 2003). So, the correlation between precipitation and urbanization varies with the geographic location of urban area. Besides, the aerodynamic mechanism of urban vegetation alters the precipitation patterns of urban clusters.

Health impacts: Various respiratory problems can be caused by UHI effect due to degraded air quality by certain cooling agents (Liu and Zhang, 2011). Thermal discomfort among urban inhabitants due to elevated urban temperature by UHI effect is quite common. The increased urban temperature due to UHI effect also leads to skin problems, heat waves and can even lead to increased mortality rates (Changnon *et al*., 1996; Hondula and Barnett, 2014).

Energy impacts: UHI is known to disturb the entire energy balance of the city. Urban factors such as structural features, type, and the surface of materials, vegetation cover, water bodies etc. monitors the energy consumption in urban clusters (Oke, 1982). The UHI induced urban warming in summer months elevates the energy consumption for cooling that in turn releases heat from air conditioners and hence air temperature rises more (Ohashi *et al*., 2007). The fact of the increase in energy requirement for cities with UHI formation is evident from the 32–42% higher energy needed for thermal comfort in urban buildings of London than nearby rural regions that are devoid of UHI effect. Due to urban heating, energy consumption is rising such as about 60% of electricity is consumed in cooling urban regions of Hong Kong during summer months (Giridharan *et al*., 2004). So, UHI effect favors the electricity consumption due to air conditioners used for cooling and hence economic cost also increases (Akbari *et al*., 2001). An elevation of 0.45 to 4.6% in electricity consumption with unit degree temperature rise has been observed cited in literature (Santamouris, 2015). There is almost 2–4% addition in energy requirement with every 1°C increase in temperature in urban clusters. This addition signifies that 5–10% of electricity consumed in cities is utilized in reducing the elevated temperature inside buildings (Akbari *et al*., 2001).

Remote sensing studies for UHI

Remote sensing and GIS have been widely used throughout the world for many years. The perspective of using satellite data for monitoring UHI effect have been contributed through number of studies such as monitoring urban area of Texas (Streutker, 2002), LULC and LST correlation studies (Chen *et al*., 2006) and for surface UHI studies (Rajasekar and Weng, 2009). The satellite images of different time periods are used for estimation of temporal trends of UHI. Due to application of wider spatial and temporal coverage with low price, use of satellite data is quite common and has been advantageous to monitor UHI patterns (Zhang *et al*., 2013).

The spatial resolution of different sensors in TIR (Thermal infrared region) has been mentioned in the table below:

Table 1: Spatial resolution of different satellites

Sr.no.	Type of satellite/sensor	Spatial Resolution
1.	NOAA-AVHRR	1 km
2.	Aqua-, Terra-MODIS	1 km
3.	ASTER	90 m
4.	Landsat-7 Enhanced Thematic Mapper (ETM+)	60 m
5.	Landsat-5 Thematic Mapper (TM)	120 m
6.	Envisat- AATSR	1 km

Source: (Mallick *et al*., 2008; Weng *et al*., 2004)

Moreover, various surface parameters such as vegetation, temperature, albedo etc can also be obtained by using satellite data. So, remote sensing is helpful in various UHI perspectives which would otherwise be hard to monitor by field measurements (Chakraborty *et al*., 2015). The combination of both the air temperature and LST measurements (Voogt and Oke, 2003; Garcia-Cueto *et al*., 2007) has also been used to monitor UHI that results in certain advantages and these two measurements exhibit a high correlation with each other (Schwarz *et al*., 2012). The exacerbating UHI effect has been documented for the number of countries (both developed and developing nations) throughout the world. India is one such developing nation in which the phenomenon of UHI came into light with the ongoing trend of rapid urbanization (Kalnay and Cai, 2003; DeFries and Pandey, 2010). With the rise in the world's urban population, the Indian urban population also shows the significant rising trend. The people residing in urban regions of India has increased to 377 million (2011) from 217 million (1991) (Pandey and Seto, 2015). This trend is expected to be followed in upcoming years as increase by about 500 million has been predicted during 2010–2050 according to UN report, 2012.

As stated above, numerous worldwide thermal remote sensing studies (Gallo *et al*., 1993; Lo *et al*., 1997; Gallo and Owen, 1999) have been carried out throughout the globe. Similarly, a variety of research has been done in India regarding this field; out of which some of the studies have been described as:

Diurnal variations in LST of Ahmadabad and Jaipur were analyzed by Mathew *et al.* (2018) to investigate the UHI effect using MODIS data for day and nighttime. Moderate to weak UHI effect was observed for Ahmadabad while cool island effect existed in Jaipur during the daytime. Nocturnal UHI effect was prevalent in both urban areas. The low temperature was recorded for vegetated areas implying that diurnal temperature variations occur due to different LULC and variable thermal properties of surface materials.

Remote sensing and GIS techniques were used by Sultana and Satyanarayana (2018) to explore UHI effect for Indian metropolitan cities. The spatial pattern of LULC and its correlation with LST was determined using Landsat 7 ETM+ data (2001-2013). The existence of multiple UHIs and increase in there number was determined using LST and LULC classification. Increase in the built-up area was noticed for the study area that leads to higher temperature zones. The metropolitan cities (Hyderabad, Nagpur and Mumbai) were observed to have high UHI intensity of 8.9–10.3°C.

Yadav and Sharma (2018) studied spatial variations in intra-urban UHI effect by the mobile transverse technique for Delhi. The air temperature was recorded for monsoon and winter months (2014) using temperature data loggers installed on a vehicle. The high intra-urban variations of magnitude 6°C were observed for the region. Seasonal variations depicted high UHI effect for winters and low for monsoon season. Nocturnal UHI effect was more pronounced than that of morning and afternoon.

Aslam *et al*. (2017) discussed seasonal (May and December, 2013) changes in UHI effect and influence of this effect on air quality in Delhi. The observational data of System of Air Quality Forecasting and Research was used in the study. UHI effect of about 1.5°C (December) and 2.2°C (May) was observed during evening time while daytime exhibited formation of the urban cool island (UCI). A bimodal pattern was observed for diurnal $PM_{2.5}$ concentration with maximum value during morning and evening traffic hours for both seasons. High wind speed was observed for cool island occurrence while wind speed was low during UHI effect. The important role of $PM_{2.5}$ was observed by regression analysis in cooling at daytime and nocturnal heating. So, higher $PM_{2.5}$ concentration for low wind speed supports UCI formation.

A field study was conducted by Kumar *et al*. (2017) for investigation of UHI in Andhra Pradesh, India. Infrared thermometers were used for temperature estimation at 212 locations for May 2016. The map for spatial variations in LST was prepared using Inverse Distance Weighted method in spatial analyst tool of ArcGIS software. The study concluded with the formation of UHI for built-up regions as vegetated areas were observed to have lower temperatures than the built-up regions of cities.

Mukherjee *et al*. (2017) analyzed surface UHI for twelve districts of Punjab, India using downscaled MODIS satellite data. The downscaled LST from 1000m to 250m depicts the temperature fluctuations between urban built-up and surrounding area, because of variable land use, more clearly. So, the finer resolution described higher intra-pixel variability. The study concluded by finding higher temperature recorded for dense built-up areas (38.87°C) inside city than suburban areas (35.85°C) followed by the rural areas (32.41°C).

Shastri *et al*. (2017) monitored diurnal and seasonal (summer and winter) patterns of SUHII in 84 urban areas in India using MODIS LST data. Negative daytime SUHI effect was observed for most of the urban areas for pre-monsoon summer months. This was because of sparse vegetation in rural areas for dry season resulting in lower evapotranspiration. While prominent SUHI effect was observed at nighttime. UHI effect was also observed for daytime in winter months. The seasonal and diurnal variations in UHI trend were attributed to evapotranspiration difference due to alterations in vegetation.

Singh *et al*. (2017) studied the influence of urbanization on UHI effect for Lucknow, using remote sensing data. LST was estimated using the mono-window algorithm for Landsat data. The study revealed that the variations in LST were due to changes in LULC as the high temperature was observed for dense built-up areas than surrounding vegetated areas. The study also analyzed the strong correlation between NDVI and LST. The worst ecological index was estimated for the core of urban clusters.

Yadav *et al*. (2017) estimated UHI and its impact on energy requirement and atmospheric chemistry for Delhi, based on meteorological data (2010–2013). LULC maps of the region were prepared in ERDAS Imagine and ArcGIS software using multispectral LISS-IV (Linear Imaging Self Scanning) images to find the influence of LULC along with wind speed and relative humidity on UHI. Day and nighttime UHIs were observed for the study area with the highest UHI intensity during morning time. UHI values were comparatively low for monsoon season. UHI effect was sustained by higher impervious surfaces, low vegetation and thus, low NDVI values. Furthermore, the UHI effect was found to decrease with wind speed. Intra-city temperature variations of 0.2–3°C were observed for the study area. Although no significant influence of UHI was observed on ozone concentration.

Berwal *et al*. (2016) studied the thermal inertia during summer season using satellite data (MODIS) for Delhi. The diurnal temperature and albedo maps prepared using satellite data were used to analyze thermal inertia for the study region. The study depicted lower temperature of Delhi comparative to its nearby rural area for daytime while heat island effect was observed for nighttime. Higher thermal inertia was observed in the summer season for the dense urban infrastructure of Delhi comparative to its surrounding rural areas. The existence of daytime UCI for Delhi was explained by the spatial pattern of thermal inertia.

The spatial variations in temperature and corresponding UHI effect were studied by Jeganathan *et al.* (2016) for Chennai, India. The air temperature was recorded by mobile measurements in the urban area for study sites made by grid network. The LULC map of the study area was prepared by digitization in ArcGIS 9.2 software of LISS III image after processing in ERDAS IMAGINE 9.3. Highest UHI intensity was observed for core of urban area with dense population. The temperature difference of 3–4.5 °C was observed for city cores and its outer parts in the morning. The important contribution of green area (estimated by NDVI) and type of land use in microclimate was recognized. A negative correlation was also estimated between green cover and microclimate change.

In another geospatial approach, multi-temporal satellite data (Landsat data for 2000, 2013), meteorological and field observations were used for estimation of temporal trends of UHI in Noida, India by Kikon *et al*. (2016). The research included the use of certain indices i.e. NDVI and NDBI for vegetation and built-up area respectively. A negative correlation was examined between emissivity, temperature and NDVI while albedo, temperature and NDBI showed the positive correlation. Increase in impervious surfaces was observed as the chief reason behind temperature variations.

Mathew *et al*. (2016) studied the spatio-temporal pattern of UHI effect for Chandigarh, India by analyzing LST for five years period (2009–13). The factors (ISA, elevation) influencing LST were also estimated. Seasonal changes were observed in the intensity of UHI effect. The increase in mean annual UHI intensity was observed from 2009 (4.98°K) to 2013 (5.43°K) with the total average of 5.2°K. UHI index was estimated to show the maximum value of 0.93. The correlation for the study area was determined for %ISA, elevation and LST. LST and %ISA were estimated to show the positive correlation which does not fluctuate with seasonal variations. The study examined the important role of elevation in LST distribution as the increase in temperature was recorded with the increase in elevation.

The remote sensing study was done by Chakraborty *et al*. (2015) to investigate the LST and heat fluxes for Delhi. Landsat and MODIS data were used for winter and summer months (2000, 2010) to determine LST and surface emissivity for different land use/land cover classes. The increase in the residential and industrial area was observed that consequently posed an influence on LST and heat fluxes. The rise in the anthropogenic heat was estimated by energy balance model. Landsat satellite data was found to be closely related with field measurements than MODIS data. The anthropogenic heat was estimated as an indicator of UHI effect for the current study.

A comparative analysis for two Indian megacities (Mumbai and Delhi) was conducted by Grover and Singh (2015) for investigation of UHI pattern using satellite data (Landsat 5 TM image). The study revealed that barren land surface and built-up areas have higher temperature than the vegetated surfaces computed using NDVI. The rising temperature of urban clusters was attributed to the loss of vegetation cover and rising urban sprawl. The higher temperature was recorded for Mumbai than Delhi because of higher infrastructure with low space and lack of vegetation in Mumbai.

Borbora and Das (2014) estimated UHI for summer months in Guwahati, India. The temperature was recorded at an interval of 30 minutes for two urban and two rural sites from May to October 2009 for estimation of urban-rural temperature contrast. The highest UHI estimated for daytime and nighttime was 2.12°C and 2.29°C, respectively.

Intra-urban variations taken by mobile measurements lie from 0.78 to 1.23°C. High diurnal temperature fluctuations were observed for each month in the study area.

Pandey *et al*. (2014) estimated spatial and temporal variations in UHI for Delhi, India. The UHI was compared with variations in land cover and aerosol load over the region. The MODIS satellite data and sun-photometer observations were used for AOD estimation. The nocturnal UHI of magnitude 4–6°K was observed for March and 0–2°K for monsoon months. But for daytime, there exists a cool island during October–December and May–June. A significant negative correlation was analyzed for UHI and aerosol optical depth implying cool island formation during daytime at higher aerosol concentrations.

Sharma and Joshi (2014) analyzed seasonal changes in the spatial trend of UHI effect using satellite data, for Delhi. Landsat TM data (2010–2011) was used for estimation of the influence of LULC on seasonal UHI patterns. Maximum UHI intensity was estimated for summer (16.7°C) while winters showed minimum UHI intensity (7.4°C). Higher UHI effect was determined in the industrial area, commercial centers and airport region.

Mohan *et al*. (2012) made an attempt to investigate the UHI effect for urban airshed in Delhi, India. A field campaign named DELHI- I was carried out for monitoring UHI in Delhi during summer months of year 2008. The dense built-up areas were found to show higher UHI effect both for the daytime and nighttime (8.3°C). The field data results were comparative to satellite data (MODIS-TERRA) for nocturnal UHI.

Landsat ETM+ image was used by Kumar *et al*. (2012) for determination of LST to monitor UHI effect in Andhra Pradesh. Supervised classification was done in ERDAS imagine software using maximum likelihood classification algorithm for Landsat data. Built–up urban areas were found to show high air temperature while the low temperature was recorded for vegetated areas. The negative correlation was observed between NDVI and LST.

Remote sensing based study was done by Ambinakudige (2011) in Bangalore to analyze the impact of land cover on UHI effect. Landsat ETM+ data were used for LST and NDVI estimation. The core of the urban cluster was observed to have lower temperature comparative to its outskirts due to the existence of vegetation and water surfaces inside the city. With the variable LULC inside the urban region, intra-urban temperature variations of 1–7°C were observed.

Amirtham *et al*. (2009) mapped micro-UHIs and variations in land cover for Chennai, India. The Landsat TM and ETM+ data (1991, 2000) was used to study the correlation between LST and LULC. LULC mapping was done by supervised classification with maximum likelihood algorithm. LST for UHI was computed using thermal bands of Landsat satellite data. The study revealed reduced vegetation and rise in the buildings for the study area. The variations in temperature were observed for variable land use types.

Katpatal *et al*. (2008) conducted remote sensing based study for estimation of air and surface temperature of Nagpur. Landsat 5 TM data (2000) was used to investigate impact of LULC on temperature in an urban area. Air temperature was found to be regulated by surface temperature while both of these temperatures were associated with type of LULC in the urban area.

Mallick *et al*. (2008) investigated LST using Landsat–7 ETM+ (1999) for Delhi. The variations among LST were compared with different types of LULC. LST and NDVI showed a strong correlation but the moderate correlation was observed between LST and fractional vegetation cover for the study area.

Mitigation

From the causes and consequences discussed above and the literature reviewed, the ground behind the formation of the UHI phenomenon is apparent. So, the mitigation measures for UHI effect can be stated as follows:

Building characteristics: Different building characteristics can again be categorized as follows:

Blue spaces: Increasing the albedo of roofs and pavements in urban areas is effective mitigation measurement of UHI effect. The reasonable increase in albedo can result in temperature decrease by 2°C–4°C (Taha, 1997). Furthermore, use of permeable urban surfaces with modified thermal characteristics can contribute a lot to UHI mitigation.

Cool pavements: Most of the light color pavement surfaces with high albedo reflect a larger portion of incident light than dark surfaces consequently leading to cool air (Akbari *et al*., 2009). The establishment of cool pavements results in the reduction of sensible heat emitted into the atmosphere with a temperature drop of about 1.5°C. The use of cool new asphalt can cause ambient temperature reduction by 1.5°C and a peak decrease in temperature can be by 11.5°C (Kyriakodis and Santamouris, 2018).

Green buildings*:* The growth of vegetation on rooftops decreases the concentration of heat over the buildings and provides atmospheric cooling. Green roofs also extend the lifespan of materials used in roofs and decrease air pollutant concentration. Besides, green walls act as an effective UHI mitigation measure as they can significantly decrease urban temperature.

Adequate urban geometry: Giant buildings and complex structure of the cities enhances the atmospheric warming accompanied with several anthropogenic activities and concentrate solar radiations within the structures (Gago *et al*., 2013). So, manipulations in urban geometry such as urban buildings with less height and density can increase sky view factor and radiative cooling can take place during nighttime. Also, wind circulations from rural areas will cool urban regions rapidly. Proper building ventilation can lower 10% cooling energy requirement (Kolokotroni *et al*., 2012).

Green cover: Increasing area under green cover (green spaces, plants, vegetation) by afforestation is a promising mitigation measure of UHI as it increases the rate of evapotranspiration and hence cooling of the region. The cooling effect of the urban vegetation relies on the cooling ability of the plant and density of foliage (Tan *et al*., 2010). The decrease in building temperature can be brought by creating green space (parks) or by planting more trees in urban buildings. Trees provide shade and cooling facility to these urban buildings through interception of incoming solar flux and averting them to infiltrate into street canyons (Matzarakis *et al*., 1999).

Water bodies: Like the green cover, water bodies also decrease the temperature by evaporation. High heat storage capacity of water will lower urban temperature. The cooling by 1–3°C up to distance of about 30–35 m has been observed, by water surfaces (Kleerekoper *et al*., 2012).

Decrease in anthropogenic heat: The regulation of industrial, vehicular, air conditioners and other heat emissions in an urban area that accelerates the UHI effect can lower down the temperature of an urban region.

The mitigation of UHI ultimately results in the reduction of power consumption and thus carbon emissions (Rizwan *et al*., 2008). So, with the rising urban sprawl and hence UHI effect, early mitigation measures are recommended for urban heat island effect to avoid catastrophic atmospheric alterations expected in near future (Weng and Yang, 2004; Larsen, 2015).

Conclusion

The eminent phenomenon of UHI is a prime factor for the depletion of environmental quality with rising energy requirement and hydrological alterations. The study revealed that reduction of area under vegetation; water bodies and increase in the built-up area are major LULC changes associated with expanding cities that culminate into drastically rising UHI effect. Thus, the variations in properties of urban surfaces causing less cooling due to reduced evaporation and higher absorption of solar insolation are the fact behind UHI occurrence. So, the study of the dynamic and spatial expansion of urban sprawl is imperative in recent times throughout the world for the better understanding of UHI parameters for climate studies.

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References

Akbari, H., Pomerantz, M., Taha, H., 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy* 70, 295-310.

Alonso, M.S., Fidalgo, M.R., Labajo, J.L., 2007. The urban heat island in Salamanca (Spain) and its relationship to meteorological parameters. *Climate Research* 34, 39-46.

Ambinakudige, S., 2011. Remote sensing of land cover's effect on surface temperatures: a case study of the urban heat island in Bangalore, India. *Applied GIS* 7.

Amirtham, L.R., Devadas, M.D., Perumal, M., 2009.Mapping of micro-urban heat islands and land cover changes: a case in Chennai City, India. *Int J Clim Chang: Impacts Response*1, 71-84.

Arnfield, A.J., 1990. Canyon geometry, the urban fabric and nocturnal cooling: a simulation approach. *Physical Geography* 11, 220-239.

Arnfield, A.J., 2003. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology* 23, 1-26.

Aslam, M.Y., Krishna, K.R., Beig, G., Tinmaker, M.I.R., Chate, D.M., 2017. Seasonal variation of urban heat island and its impact on air-quality using SAFAR observations at Delhi, India. *American Journal of Climate Change* 6, 294-305.

Baik, J.J., Kim, Y.H., Chun, H.Y., 2001. Dry and moist convection forced by an urban heat island. *Journal of Applied Meteorology* 40, 1462-1475.

Baker, L.A., Brazel, A.J., Selover, N., Martin, C., McIntyre, N., Steiner, F.R., Nelson, A., Musacchio, L., 2002. Urbanization and warming of Phoenix (Arizona, USA): Impacts, feedbacks and mitigation. *Urban Ecosystems* 6, 183-203.

Berwal, S., Kumar, D., Pandey, A.K., Singh, V.P., Kumar, R., Kumar, K., 2016. Dynamics of thermal inertia over highly urban city: a case study of Delhi. In *Remote Sensing Technologies and Applications in Urban Environments* pp. 100080E.International Society for Optics and Photonics.

Böhm, R., 1998. Urban bias in temperature time series–A case study for the city of Vienna, Austria. *Climatic Change* 38, 113-128.

Borbora, J., Das, A.K., 2014. Summertime urban heat island study for Guwahati city, India. *Sustainable Cities and Society* 11, 61-66.

Bottyán, Z., Unger, J., 2003. A multiple linear statistical model for estimating the mean maximum urban heat island. *Theoretical and Applied Climatology* 75, 233-243.

Burian, S.J., Shepherd, J.M., 2005.Effect of urbanization on the diurnal rainfall pattern in Houston. *Hydrological Processes: An International Journal* 19, 1089-1103.

Busato, F., Lazzarin, R.M., Noro, M., 2014. Three years of study of the Urban Heat Island in Padua: Experimental results. *Sustainable Cities and Society* 10, 251-258.

Carlson, T.N., Dodd, J.K., Benjamin, S.G., Cooper, J.N., 1981. Satellite estimation of the surface energy balance, moisture availability and thermal inertia. *Journal of Applied Meteorology* 20, 67-87.

Chadchan, J., Shankar, R., 2012. An analysis of urban growth trends in the post-economic reforms period in India. *International Journal of Sustainable Built Environment* 1, 36-49.

Chakraborty, S.D., Kant, Y., Mitra, D., 2015. Assessment of land surface temperature and heat fluxes over Delhi using remote sensing data. *Journal of Environmental Management* 148, 143-152.

Changnon, S.A., Kunkel, K.E., Reinke, B.C., 1996. Impacts and responses to the 1995 heat wave: A call to action. *Bulletin of the American Meteorological Society* 77, 1497-1506.

Chen, L., Ng, E., An, X., Ren, C., Lee, M., Wang, U., He, Z., 2012. Sky view factor analysis of street canyons and its implications for daytime intra-urban air temperature differentials in high-rise, high-density urban areas of Hong Kong: a GIS-based simulation approach. *International Journal of Climatology* 32, 121-136.

Chen, X.L., Zhao, H.M., Li, P.X., Yin, Z.Y., 2006. Remote sensing image-based analysis of the relationship between urban heat island and land use/cover changes. *Remote Sensing of Environment* 104, 133-146.

DeFries, R., Pandey, D., 2010. Urbanization, the energy ladder and forest transitions in India's emerging economy. *Land Use Policy* 27, 130-138.

Emmanuel, R., 1997. Summertime urban heat island mitigation: propositions based on an investigation of intra-urban air temperature variations. *Architectural Science Review* 40, 155-164.

Gago, E.J., Roldan, J., Pacheco-Torres, R., Ordóñez, J., 2013. The city and urban heat islands: A review of strategies to mitigate adverse effects. *Renewable and Sustainable Energy Reviews* 25, 749-758.

Gallo, K.P., McNab, A.L., Karl, T.R., Brown, J.F., Hood, J.J., Tarpley, J.D., 1993. The use of a vegetation index for assessment of the urban heat island effect. *Remote Sensing* 14, 2223-2230.

Gallo, K.P., Owen, T.W., 1999. Satellite-based adjustments for the urban heat island temperature bias. *Journal of Applied Meteorology* 38, 806-813.

García-Cueto, O.R., Jauregui-Ostos, E., Toudert, D., Tejeda-Martinez, Adalberto., 2007. Detection of the urban heat island in Mexicali, BC, México and its relationship with land use. *Atmósfera* 20, 111-131.

Gedzelman, S.D., Austin, S., Cermak, R., Stefano, N., Partridge, S., Quesenberry, S., Robinson, D.A., 2003.Mesoscale aspects of the urban heat island around New York City. *Theoretical and Applied Climatology* 75, 29-42.

Giridharan, R., Ganesan, S., Lau, S.S.Y., 2004.Daytime urban heat island effect in high-rise and high-density residential developments in Hong Kong. *Energy and Buildings* 36, 525-534.

Grimmond, S.U.E., 2007. Urbanization and global environmental change: local effects of urban warming. *Geographical Journal* 173, 83-88.

Grover, A., Singh, R.B., 2015. Analysis of urban heat island (UHI) in relation to normalized difference vegetation index (NDVI): A comparative study of Delhi and Mumbai. *Environments* 2, 125-138.

Hawkins, T.W., Brazel, A.J., Stefanov, W.L., Bigler, W., Saffell, E.M., 2004. The role of rural variability in urban heat island determination for Phoenix, Arizona. *Journal of Applied Meteorology* 43, 476-486.

Hondula, D.M., Barnett, A.G., 2014. Heat-related morbidity in Brisbane, Australia: spatial variation and area-level predictors. *Environmental Health Perspectives*122, 831.

Howard, L., 1833. The climate of London, vols.I–III. *London: Harvey and Dorton*.

Huang, G., Zhou, W., Cadenasso, M.L., 2011. Is everyone hot in the city? Spatial pattern of land surface temperatures, land cover and neighborhood socioeconomic characteristics in Baltimore, MD. *Journal of Environmental Management* 92, 1753-1759.

Imhoff, M.L., Zhang, P., Wolfe, R.E., Bounoua, L., 2010. Remote sensing of the urban heat island effect across biomes in the continental USA. *Remote Sensing of Environment* 114, 504-513.

Jeganathan, A., Andimuthu, R., Prasannavenkatesh, R., Kumar, D.S., 2016. Spatial variation of temperature and indicative of the urban heat island in Chennai Metropolitan Area, India. *Theoretical and Applied Climatology* 123, 83-95.

Jiang, J., Tian, G., 2010. Analysis of the impact of land use/land cover change on land surface temperature with remote sensing. *Procedia Environmental Sciences* 2, 571-575.

Jiang, L., Deng, X., Seto, K.C., 2013. The impact of urban expansion on agricultural land use intensity in China. *Land Use Policy* 35, 33-39.

Jonsson, P., 2004. Vegetation as an urban climate control in the subtropical city of Gaborone, Botswana. *International Journal of Climatology* 24, 1307-1322.

Kalnay, E., Cai, M., 2003. Impact of urbanization and land-use change on climate. *Nature* 423, 528.

Karl, T.R., Diaz, H.F., Kukla, G., 1988. Urbanization: Its detection and effect in the United States climate record. *Journal of Climate* 1, 1099-1123.

Katpatal, Y.B., Kute, A., Satapathy, D.R., 2008. Surface-and air-temperature studies in relation to land use/land cover of Nagpur urban area using Landsat 5 TM data. *Journal of Urban Planning and Development* 134, 110-118.

Kaufmann, R.K., Seto, K.C., Schneider, A., Liu, Z., Zhou, L., Wang, W., 2007. Climate response to rapid urban growth: evidence of a human-induced precipitation deficit. *Journal of Climate* 20, 2299-2306.

Kikon, N., Singh, P., Singh, S. K., Vyas, A., 2016. Assessment of urban heat islands (UHI) of Noida City, India using multi-temporal satellite data. *Sustainable Cities and Society* 22, 19-28.

Kim, Y.H., Baik, J.J., 2002. Maximum urban heat island intensity in Seoul. *Journal of Applied Meteorology* 41, 651-659.

Kim, Y.H., Baik, J.J., 2004. Daily maximum urban heat island intensity in large cities of Korea. *Theoretical and Applied Climatology* 79, 151-164.

Kim, Y.H., Baik, J.J., 2005. Spatial and temporal structure of the urban heat island in Seoul. *Journal of Applied Meteorology* 44, 591-605.

Kleerekoper, L., Van Esch, M., Salcedo, T.B., 2012.How to make a city climate-proof, addressing the urban heat island effect. *Resources, Conservation and Recycling* 64, 30-38.

Kolokotroni, M., Ren, X., Davies, M., Mavrogianni, A., 2012. London's urban heat island: Impact on current and future energy consumption in office buildings. *Energy and Buildings* 47, 302-311.

Kumar, K.S., Bhaskar, P.U., Kumari, K.P., 2017. Assessment and Mapping of Urban Heat Island using Field Data in the New Capital Region of Andhra Pradesh, India. *Indian Journal of Science and Technology* 10.

Kumar, K.S., Bhaskar, P.U., Padmakumari, K., 2012. Estimation of land surface temperature to study urban heat island effect using LANDSAT ETM+ image. *International journal of Engineering Science and Technology* 4, 771-778.

Kyriakodis, G.E., Santamouris, M., 2018.Using reflective pavements to mitigate urban heat island in warm climates-results from a large scale urban mitigation project. *Urban Climate* 24, 326-339.

Larsen, L., 2015. Urban climate and adaptation strategies. *Frontiers in Ecology and the Environment* 13, 486-492.

Liu, L., Zhang, Y., 2011. Urban heat island analysis using the Landsat TM data and ASTER data: A case study in Hong Kong. *Remote Sensing* 3, 1535-1552.

Lo, C.P., Quattrochi, D.A., Luvall, J.C., 1997. Application of high-resolution thermal infrared remote sensing and GIS to assess the urban heat island effect. *International Journal of Remote Sensing* 18, 287-304.

Mallick, J., 2014. Land characterization analysis of surface temperature of semi-arid mountainous city Abha, Saudi Arabia using remote sensing and GIS. *Journal of Geographic Information System* 6, 664.

Mallick, J., Kant, Y., Bharath, B.D., 2008. Estimation of land surface temperature over Delhi using Landsat-7 ETM+. *J. Ind. Geophys. Union* 12, 131-140.

Mathew, A., Khandelwal, S., Kaul, N., 2016. Spatial and temporal variations of urban heat island effect and the effect of percentage impervious surface area and elevation on land surface temperature: Study of Chandigarh city, India. *Sustainable Cities and Society* 26, 264-277.

Mathew, A., Khandelwal, S., Kaul, N., 2018.Analysis of diurnal surface temperature variations for the assessment of surface urban heat island effect over Indian cities. *Energy and Buildings* 159, 271-295.

Matzarakis, A., Mayer, H., Iziomon, M.G., 1999. Applications of a universal thermal index: physiological equivalent temperature. *International Journal of Biometeorology* 43, 76-84.

Memon, R.A., Leung, D.Y., 2010. Impacts of environmental factors on urban heating. *Journal of Environmental Sciences* 22, 1903-1909.

Mohan, M., Kikegawa, Y., Gurjar, B.R., Bhati, S., Kandya, A., Ogawa, K., 2012. Urban heat island assessment for a tropical urban airshed in India. *Atmospheric and Climate Sciences* 2, 127-138.

Mondal, M.S., Sharma, N., Kappas, M., Garg, P.K., 2015. Critical assessment of land use land cover dynamics using multi-temporal satellite images. *Environments* 2, 61-90.

Morris, C.J.G., Simmonds, I., Plummer, N., 2001. Quantification of the influences of wind and cloud on the nocturnal urban heat island of a large city. *Journal of Applied Meteorology* 40, 169-182.

Mukherjee, S., Joshi, P.K., Garg, R.D., 2017. Analysis of urban built-up areas and surface urban heat island using downscaled MODIS derived land surface temperature data. *Geocarto International* 32, 900-918.

Nesarikar-Patki, P., Raykar-Alange, P., 2012.Study of influence of land cover on urban heat islands in pune using remote sensing. *J. Mech. Civil Eng* 3, 39-43.

Ohashi, Y., Genchi, Y., Kondo, H., Kikegawa, Y., Yoshikado, H., Hirano, Y., 2007. Influence of air-conditioning waste heat on air temperature in Tokyo during summer: numerical experiments using an urban canopy model coupled with a building energy model. *Journal of Applied Meteorology and Climatology* 46, 66-81.

Oke, T.R., 1973. City size and the urban heat island. *Atmospheric Environment (1967)* 7, 769-779.

Oke, T.R., 1976. The distinction between canopy and boundary-layer urban heat islands. *Atmosphere* 14, 268-277.

Oke, T.R., 1981. Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observations. *Journal of Climatology* 1, 237-254.

Oke, T.R., 1982. The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society* 108, 1-24.

Oke, T.R., 1987. Boundary layer climates.2nd. *Methuen, p.289*, *548*.

Oke, T.R., Johnson, G.T., Steyn, D.G., Watson, I.D., 1991. Simulation of surface urban heat islands under 'ideal'conditions at night Part 2: Diagnosis of causation. *Boundary-Layer Meteorology* 56, 339-358.

Owen, T.W., Carlson, T.N., Gillies, R.R., 1998. An assessment of satellite remotely-sensed land cover parameters in quantitatively describing the climatic effect of urbanization. *International Journal of Remote Sensing* 19, 1663-1681.

Pandey, A.K., Singh, S., Berwal, S., Kumar, D., Pandey, P., Prakash, A., Lodhi, N., Maithani, S., Jain, V.K., Kumar, K., 2014. Spatio–temporal variations of urban heat island over Delhi. *Urban Climate* 10, 119-133.

Pandey, B., Seto, K.C., 2015. Urbanization and agricultural land loss in India: Comparing satellite estimates with census data. *Journal of Environmental Management* 148, 53-66.

Papanastasiou, D.K., Kittas, C., 2012. Maximum urban heat island intensity in a medium-sized coastal Mediterranean city. *Theoretical and Applied Climatology* 107, 407-416.

Phelan, P.E., Kaloush, K., Miner, M., Golden, J., Phelan, B., Silva III, H., Taylor, R.A., 2015. Urban heat island: mechanisms, implications, and possible remedies. *Annual Review of Environment and Resources* 40, 285-307.

Rajasekar, U., Weng, Q., 2009. Spatio-temporal modelling and analysis of urban heat islands by using Landsat TM and ETM+ imagery. *International Journal of Remote Sensing* 30, 3531-3548.

Ramachandra, T.V., Bharath, A.H., Sowmyashree, M.V., 2015. Monitoring urbanization and its implications in a mega city from space: Spatiotemporal patterns and its indicators. *Journal of Environmental Management* 148, 67-81.

Rasul, A., Balzter, H., Smith, C., Remedios, J., Adamu, B., Sobrino, J.A., Srivanit, M., Weng, Q., 2017.A review on remote sensing of urban heat and cool islands. *Land* 6, 38.

Rizwan, A.M., Dennis, L.Y., Chunho, L.I.U., 2008. A review on the generation, determination and mitigation of Urban Heat Island. *Journal of Environmental Sciences* 20, 120-128.

Rosenfeld, A.H., Akbari, H., Romm, J.J., Pomerantz, M., 1998. Cool communities: strategies for heat island mitigation and smog reduction. *Energy and Buildings* 28, 51-62.

Roth, M., Chow, W.T., 2012. A historical review and assessment of urban heat island research in Singapore. *Singapore Journal of Tropical Geography* 33, 381-397.

Roth, M., Oke, T.R., Emery, W.J., 1989.Satellite-derived urban heat islands from three coastal cities and the utilization of such data in urban climatology. *International Journal of Remote Sensing*10, 1699-1720.

Rozoff, C.M., Cotton, W.R., Adegoke, J.O., 2003. Simulation of St. Louis, Missouri, land use impacts on thunderstorms. *Journal of Applied Meteorology* 42, 716-738.

Sailor, D.J., 2011.A review of methods for estimating anthropogenic heat and moisture emissions in the urban environment. *International Journal of Climatology* 31, 189-199.

Sailor, D.J., Fan, H., 2002.Modeling the diurnal variability of effective albedo for cities. *Atmospheric Environment* 36, 713-725.

Santamouris, M., 2015.Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. *Science of the Total Environment* 512, 582-598.

Santamouris, M., Papanikolaou, N., Livada, I., Koronakis, I., Georgakis, C., Argiriou, A., Assimakopoulos, D.N., 2001.On the impact of urban climate on the energy consumption of buildings. *Solar Energy* 70, 201-216.

Schwarz, N., Lautenbach, S., Seppelt, R., 2011.Exploring indicators for quantifying surface urban heat islands of European cities with MODIS land surface temperatures. *Remote Sensing of Environment* 115, 3175-3186.

Schwarz, N., Schlink, U., Franck, U., Großmann, K., 2012. Relationship of land surface and air temperatures and its implications for quantifying urban heat island indicators—An application for the city of Leipzig (Germany). *Ecological Indicators* 18, 693-704.

Sham, J.F., Lo, T.Y., Memon, S.A., 2012. Verification and application of continuous surface temperature monitoring technique for investigation of nocturnal sensible heat release characteristics by building fabrics. *Energy and Buildings* 53, 108-116.

Sharma, R., Joshi, P.K., 2014. Identifying seasonal heat islands in urban settings of Delhi (India) using remotely sensed data–An anomaly based approach. *Urban Climate* 9, 19-34.

Shastri, H., Barik, B., Ghosh, S., Venkataraman, C., Sadavarte, P., 2017. Flip flop of day-night and summer-winter surface urban heat island intensity in India. *Scientific Reports* 7, 40178.

Singh, O., Arya, P., Chaudhary, B.S., 2013. On rising temperature trends at Dehradun in Doon valley of Uttarakhand, India. *Journal of Earth System Science* 122, 613-622.

Singh, P., Kikon, N., Verma, P., 2017. Impact of land use change and urbanization on urban heat island in Lucknow city, Central India. A remote sensing based estimate. *Sustainable Cities and Society* 32, 100-114.

Stewart, I.D., 2011. A systematic review and scientific critique of methodology in modern urban heat island literature. *International Journal of Climatology* 31, 200-217.

Streutker, D.R., 2002. A remote sensing study of the urban heat island of Houston, Texas. *International Journal of Remote Sensing* 23, 2595-2608.

Sultana, S., Satyanarayana, A.N.V., 2018. Urban heat island intensity during winter over metropolitan cities of India using remote-sensing techniques: impact of urbanization. *International Journal of Remote Sensing*, 1-39.

Svensson, M.K., Eliasson, I., 2002. Diurnal air temperatures in built-up areas in relation to urban planning.*Landscape and Urban Planning* 61, 37-54.

Taha, H., 1997. Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat. *Energy and Buildings* 25, 99-103.

Tan, J., Zheng, Y., Tang, X., Guo, C., Li, L., Song, G., Zhen, X., Yuan, D., Kalkstein, A.J., Li, F., Chen, H., 2010.The urban heat island and its impact on heat waves and human health in Shanghai. *International Journal of Biometeorology* 54, 75-84.

Thielen, J., Wobrock, W., Gadian, A., Mestayer, P.G., Creutin, J.D., 2000. The possible influence of urban surfaces on rainfall development: a sensitivity study in 2D in the meso-γ-scale. *Atmospheric Research* 54, 15-39.

Thorsson, S., Lindberg, F., Björklund, J., Holmer, B., Rayner, D., 2011. Potential changes in outdoor thermal comfort conditions in Gothenburg, Sweden due to climate change: the influence of urban geometry. *International Journal of Climatology* 31, 324-335.

United Nations.Department of Economic and Social Affairs.Population Division. (2012). *World urbanization prospects: The 2011 revision*. UN.

Voogt, J.A., Oke, T.R., 2003. Thermal remote sensing of urban climates. *Remote Sensing of Environment* 86, 370-384.

Weng, Q., Lu, D., Schubring, J., 2004. Estimation of land surface temperature–vegetation abundance relationship for urban heat island studies. *Remote sensing of Environment* 89, 467-483.

Weng, Q., Yang, S., 2004. Managing the adverse thermal effects of urban development in a densely populated Chinese city. *Journal of Environmental Management* 70, 145-156.

Yadav, N., Sharma, C., 2018. Spatial variations of intra-city urban heat island in megacity Delhi. *Sustainable Cities and Society* 37, 298-306.

Yadav, N., Sharma, C., Peshin, S.K., Masiwal, R., 2017. Study of intra-city urban heat island intensity and its influence on atmospheric chemistry and energy consumption in Delhi. *Sustainable Cities and Society* 32, 202-211.

Yan, Z.W., Wang, J., Xia, J.J., Feng, J.M., 2016. Review of recent studies of the climatic effects of urbanization in China. *Advances in Climate Change Research* 7, 154-168.

Yuan, F., Bauer, M.E., 2007. Comparison of impervious surface area and normalized difference vegetation index as indicators of surface urban heat island effects in Landsat imagery. *Remote Sensing of Environment* 106, 375-386.

Zha, Y., Gao, J., Ni, S., 2003. Use of normalized difference built-up index in automatically mapping urban areas from TM imagery. *International Journal of Remote Sensing* 24, 583-594.

Zhang, H., Qi, Z.F., Ye, X.Y., Cai, Y.B., Ma, W.C., Chen, M.N., 2013. Analysis of land use/land cover change, population shift, and their effects on spatiotemporal patterns of urban heat islands in metropolitan Shanghai, China. *Applied Geography* 44,121-133.