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Urban Heat Island studies: Current status in India and a comparison with the International studies

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Urbanization has resulted in many critical issues like increase in pollution levels, sudden climatic changes and the rise of temperature in the urban area, that is the formation of Urban Heat Islands (UHI). As the density of population rises, most of the land areas are being converted into cities and cities grows very rapidly. Due to the UHI effect, the cities are becoming hotter day by day. In India, all the metropolitan cities are victims of UHI effect and the severity of heat formation, necessitates research in this area. The present paper evaluates the trends of UHI studies in Indian cities and its out reach till 2018. Heat Island classification, methods of studying UHI in India and their limitation are discussed. Eventually a comparison of new trends of UHI studies in the world and where India lacks its growth in UHI research are included in this paper. One of the findings is that numerical modelling studies are very limited in India in this field and more focus in this area is required.

Keywords. Urbanization; Urban Heat Islands; numerical modelling.

1. Introduction

The world today is facing many environmental problems such as global warming, air pollution, extinction of animal and plant species, contamination of soil and water bodies and sudden climatic changes. Urbanization has been attributed to these environmental issues globally for past two decades. Population increases along with the economic growth and consumption of fossil fuels is having a linear relation with the population rise. Increased consumption of fossil fuels finally gives the by-products for greenhouse gas (GHG) effect. Even though around three by fourth of earth's surface area is covered by water, still the world faces scarcity of potable water. The water bodies are getting contaminated due to dumping of urban garbage, oil spills, commercial and industrial waste, etc. and as a consequence, the marine plants and animals are in the verge of endanger. The unanticipated climatic changes we are facing today is never due to natural processes, but only due to the unnecessary intervention of the human activities as a part of urbanization. Increase in fuel usage, waste disposal, high level usage of concrete, deforestation and greenhouse gas emission leads to the urban heat islands, global warming, flood, heavy rain fall, melting of polar ice caps and many more. These climatic effects have more harmful outcomes such as restructuring of ecosystems, inhibition to the growth of animals and plants, increase in epidemics, rise in human health issues, etc. Therefore, understanding the causes of these climatic problems and finding solution for these have become part of every country's research and

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developmental programmes. Rise in temperature is a serious issue faced by the world due to fast growth in conversion of land areas into cities. The UHI effect is mainly caused by reduced sky view factors, materials with high heat capacity, anthropogenic heat, lack of evapotranspiration and reduced turbulent convection as per Blocken (2015) and Nakata-osaki *et al.* (2015). According to them, UHI influencing parameters are wind, solar radiation, anthropogenic heat, sky view factor, urban canopy, building material, building ventilation, type of land surfaces, etc. Changes in these parameters are considered for evaluating the heat intensity at a particular location.

It was Luke Howard, who pioneered the microclimatic study when history of urban climatology is examined. His contributions are evident in his book 'The Climate of London, deduced from Meteorological Observations, made at different places in the Neighbourhood of the Metropolis', Vol I, published in 1818 (Luke 1818). Howard conducted experiments to study the climate of a city and his findings are the base for the researchers who are concerned with the urban climatic study (Mills 2008, 2009, 2014). In 1937, Albert Kratzer published the first edition of his book 'The climate of Cities (Das Stadtklima)' (Kratzer 1937, 1956) which gives motivation for urban climate study. There are many followers afterwards including Helmut E Landsberg the author of the book 'The Urban Climate', published in 1981 (Landsberg 1981). The modern era or history of urban climatic study was initiated by Tim Oke. In the paper, Oke (2006) describes eight modes of investigation or practice employed in the Urban Climatology: Conceptualization, Theorization, Field observation, Modelling (statistical, scale and numerical), Validation of models, Application in urban design and planning, Impact assessment (post-implementation) and Policy development and modification. As it was initiated from the conceptual form to theoretical form, the modern climatic work is in the stage of well representing all the first four modes of investigation. There are well established models, but still validation of models is in its developmental stage, which requires prime importance. According to Oke, proper communication between all the eight modes are essential for the functioning of urban climatology study with minimal errors. The challenge lies in transferring the acquired scientific knowledge into practice through proper designing and planning as well as modifying the existing policies accordingly. He believes the future prospectus is in connecting the scattered researchers to reduce the solitude and engaging them for an effective communication (Mills 2014).

2. Increasing Heat Island formation in Indian cities

Urbanization that results in the formation of heat pockets or UHI which rises near surface air temperature has become a serious issue in the Indian cities also. As cities are increasing in its size, the local climate also gets modified accordingly. As per Sharma and Bharat (2009), the causes of change in the city climate is due to albedo, changes in the shape of the city and the sky view factor related to that, air pollution and anthropogenic heat due to human activities, industries, vehicles, etc.

The reports showed that mean maximum heat island intensity observed in Chennai city has been 2.48°C during summers and 3.35°C during winters. A study carried out in IISc, Bangalore (Ramachandra and Kumar 2010) showed an increase of nearly 2°–2.5°C in air temperatures in the past decade and it also showed a growth of 632% in urban area of Bangalore from 1973 to 2009. Another study conducted by IIT Delhi in Delhi city has found the maximum and minimum heat island intensity to reach temperatures of 8.3° and 4.7°C, respectively. A rise of 1°−6°C has been shown in land surface temperatures from the year 1999 to 2006 in the studies conducted in Pune. The reports show internationally the maximum UHI intensity recorded is as high as 12° and in India the maximum observed UHI intensity is 8−9°C. So the after effect of heat island formation is that there is notable increase in energy and water consumption, increased emission of pollutants to the atmosphere leading into greenhouse effect, heat-related discomfort in health and life, degradation in water quality of streams, rivers and other water bodies (Jain and Sarkar 2017). Jain and Sarkar (2017) gave the strategies for reducing the UHI effect as by improving the vegetation cover, constructing green walls and roofs, increasing the reflectivity (albedo) and emissivity of the building material, utilising passive cooling methods in buildings and by reducing the anthropogenic heat production sources. Lack of public education and outreach is another reason for increase in heat intensity (Sharma and Bharat 2009). So policies should be made to balance the microclimate of cities and should be properly communicated to the public.

This research article is based on 37 papers collected on the UHI studies conducted in different parts of Indian cities. From the papers, it is found that majority of the studies are concentrated towards the capital city. About 30% of the collected papers include the heat island formation in Delhi area, and the causes and effects of it. After Delhi, Bangalore is the second city where the UHI studies are focussed more. Table 1 shows the year-wise list of papers collected and the corresponding cities of studies. The locations of UHI studies in India is marked in the map as shown in figure 1.

Based on the collected papers it can be deduced that in India UHI studies were initiated in the early 20th century.

Table 1 shows the list of studies carried out for finding the heat island formation in different parts of India from the year 2000 to 2018. The first paper on heat island intensity found was based on the temperature increase in Pune, Maharashtra in the year 2000 (Deosthali 2000). As mentioned above, majority of the studies are concentrated on the capital city, New Delhi (Mohan *et al.* 2012; Pandey *et al.* 2012; Babazadeh and Kumar 2015; Aslam *et al.* 2017) and the other cities where UHI studies were carried out are Bangalore (Gopalakrishnan *et al.* 2003; Ramachandra and Kumar 2010; Ambinakudige 2011), Mumbai (Grover and Singh 2015; Mehrotra 2018), Chennai (Gopalakrishnan *et al.* 2003; Amirtham 2016), Pune (Deosthali 2000; Nesarikar-Patki and Raykar-Alange 2012), Hyderabad (Gopalakrishnan *et al.* 2003), Ahmedabad

Table 1. *UHI studies in Indian cities.*

Sl. no.	Year	Study location	Paper
1	2000	Pune, Maharashtra	Deosthali (2000)
2	2003	Chennai, Bangalore, Hyderabad	Gopalakrishnan *et al.* (2003)
3	2006	Visakhapatnam, Andhra Pradesh	Devi (2006)
4	2009	Bhopal, Madhya Pradesh	Gupta *et al.* (2009)
5	2010	Bangalore, Karnataka	Ramachandra and Kumar (2010)
6	2011	Delhi	Mohan *et al.* (2011)
7	2011	Delhi	Ahmad *et al.* (2011)
8	2011	Bangalore, Karnataka	Ambinakudige (2011)
9	2012	Delhi	Mohan *et al.* (2012)
10	2012	Pune, Maharashtra	Nesarikar-Patki and Raykar-Alange (2012)
11	2012	Delhi	Pandey *et al.* (2012)
12	2012	Jaipur, Rajasthan	Gupta (2012)
13	2013	Delhi	Mohan *et al.* (2013)
14	2014	Kochi, Kerala	Thomas *et al.* (2014)
15	2014	Guwahati, Assam	Borbora and Das (2014)
16	2015	Bathinda, Punjab	Sharma and Pandey (2015)
17	2015	Thiruchirappalli, Tamil Nadu	Kannamma and Sundaram (2015)
18	2015	Delhi and Mumbai, Maharashtra	Grover and Singh (2015)
19	2015	Delhi	Babazadeh and Kumar (2015)
20	2015	Ahmedabad, Gujarat	Joshi *et al.* (2015)
21	2016	Ernakulam, Kerala	Baby and Arya (2016)
22	2016	Chennai, Tamil Nadu	Amirtham (2016)
23	2016	Uttarakhand	Kumar and Singh (2016)
24	2016	Ahmedabad, Gujarat	Goswami *et al.* (2016)
25	2016	Bhubaneswar, Odisha	Swain *et al.* (2016)
26	2016	Noida, Uttar Pradesh	Kikon *et al.* (2016)
27	2016	Kanpur, Uttar Pradesh	Chakraborty *et al.* (2016)
28	2017	Lucknow, Uttar Pradesh	Singh *et al.* (2017)
29	2017	Delhi	Aslam *et al.* (2017)
30	2017	Andhra Pradesh	Kumar *et al.* (2017a)
31	2018	Mumbai, Maharashtra	Mehrotra (2018)
32	2018	Kolkata, West Bengal	Ali Gazi and Mondal (2018)

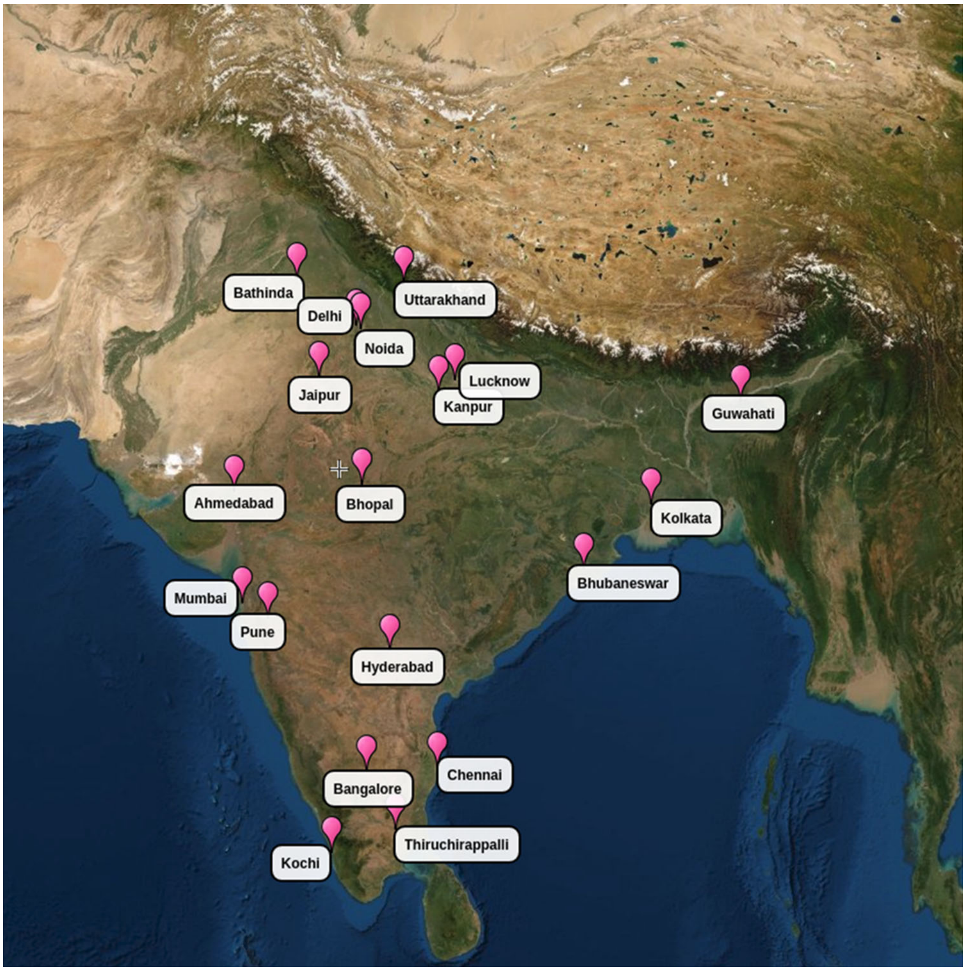

Figure 1. UHI studies conducted in Indian cities (map made using scribble maps).

(Joshi *et al.* 2015; Goswami *et al.* 2016), Visakhapatnam (Devi 2006), Ernakulam (Baby and Arya 2016; Thomas *et al.* 2014), Bhopal (Gupta *et al.* 2009), Bhubaneswar (Swain *et al.* 2016), Noida (Kikon *et al.* 2016), Kanpur (Chakraborty *et al.* 2016), Lucknow (Singh *et al.* 2017), Bathinda (Sharma and Pandey 2015), Guwahati (Borbora and Das 2014), Jaipur (Gupta 2012), Kolkata (Ali Gazi and Mondal 2018), Thiruchirappalli (Kannamma and Sundaram 2015) and Uttarakhand (Kumar and Singh 2016).

3. Urban Heat Island definition and classification

As per definition, the higher temperature observed in the cities in comparison with the surrounding rural area is called as Urban Heat Islands (Luke 1818). In similar way, an occasional lower temperature observed in cities are called Urban Cool Islands. Urban Heat Island Intensity (UHII) is the index showing the presence of UHI. It is determined as the spatially averaged temperature difference between an urban and its surrounding rural area. But some reports are based on the difference between the air and surface temperatures. The UHI determined by comparing the 'mean' and 'maximum' temperature in between rural and urban area referred to as the 'mean' and 'maximum' UHI, respectively. The comparison time period varies from within a day, a few selected days, a month, a season and a year to even decades.

There are two main classifications of UHI: Atmospheric Heat Island (AHI) and Surface Heat Island (SHI). Most of the collected studies are based on SHI which employs the use of thermal satellite images, remote sensing, GIS tools, etc. SHI exists at all times. AHI is predominant at night and insignificant during day time. Fixed weather stations and mobile traverses are used to measure AHI intensity. Computational studies and experimental studies are more concentrated towards finding

Table 2. *Period of UHI study in various studies.*

Sl. no.	Paper	Study period	Duration	Variable
1	Mohan *et al.* (2011)	1968–2005	37 years	AT
2	Swain *et al.* (2016)	2000–2014	15 years	LST
3	Babazadeh and Kumar (2015)	2000–2014	14 years	LST
4	Kikon *et al.* (2016)	2000–2013	13 years	LST
5	Kumar *et al.* (2017b)	2003-2014	12 years	LST
6	Goswami *et al.* (2016)	2003–2014	12 years	ST
7	Devi (2006)	–	10 years	ST
8	Ramachandra and Kumar (2010)	–	10 years	AT, LST
9	Nesarikar-Patki and Raykar-Alange (2012)	1999–2006	7 years	LST
10	Thomas *et al.* (2014)	Jan 2011–Mar 2013	2 years and 3 months	AT
11	Gopalakrishnan *et al.* (2003)	2001, 2002	2 years	AT, ST
12	Gupta *et al.* (2009)	2006	1 year	ST
13	Gupta (2012)	between 2001 and 2009	–	ST
14	Amirtham (2016)	May 2008 to Jan 2009	9 months	AT
15	Pandey *et al.* (2012)	Nov and Dec of 2007–2010	8 months	ST
16	Borbora and Das (2014)	May–Oct 2009	6 months	AT
17	Shastri *et al.* (2017)	Mar–May and Dec–Feb	6 months	LST
18	Chakraborty *et al.* (2016)	Apr–Sept 2014	6 months	LST, AT
19	Sharma and Pandey (2015)	Feb–Apr 2015	3 months	ST
20	Aslam *et al.* (2017)	May and Dec 2013	2 months	AT
21	Baby and Arya (2016)	Oct 2015	1 month	AT
22	Deosthali (2000)	Apr 1970	1 month	AT
23	Kumar *et al.* (2017a)	May 2016	1 month	LST
24	Mohan *et al.* (2013)	6–13 Mar 2010	7–8 days	LST
25	Mohan *et al.* (2012)	25–28 May 2008	3 days	LST, AT
26	Ambinakudige (2011)	16 Mar 2000 and 09 Mar 2003	2 days	LST
27	Grover and Singh (2015)	05 May 2010 and 17 Apr 2010	2 days	LST
28	Kannamma and Sundaram (2015)	May 2014	1 day	PET
29	Ahmad *et al.* (2011)	26 Jun 2006	1 day	LST
30	Mehrotra (2018)	20 Oct 2016	1 day	ST

LST = Land Surface Temperature, AT = Air Temperature, ST = Surface Temperature, PET = Physiological Equivalent Temperature.

AHI. AHI is again classified into two: Canopy Layer Heat Island (CLHI), present in the air between the roughness components with an upper boundary below the roof level and Boundary Layer Heat Island (BLHI), situated above CLHI.

Among the papers, more than 70% of the studies are related to Land Surface Temperature (LST) and Surface Temperatue (ST) analysis (i.e., Surface Heat Island study) and about 30% of studies are only on AHI. Table 2 shows the duration of UHI study in each paper along with the temperature variable used to define UHI and table 3 shows the magnitude of UHI intensity and the method of study adopted to calculate UHII.

Mohan *et al.* (2011) have found out the annual mean maximum temperature difference between the national capital region of India for a duration of 37 yrs. Here, when Mohan *et al.* (2011) found out the UHI intensity based on the annual mean and maximum temperature in the city, Swain *et al.* (2016) estimates UHI from the difference in the LST between urbanized and non-urbanized pixels from the MODIS data for the city of Bhubaneswar for a 15 yrs' period from 2000 to 2014. In Babazadeh and Kumar (2015) studies, UHI intensity during summer, winter and monsoon months are compared during the year from 2000 to 2014. It was found that intensity is high during summer season and the heat island intensity varies from 3° to 8°C. Likewise, Devi (2006), Ramachandra and Kumar (2010), Goswami *et al.* (2016), Kikon *et al.* (2016) studied UHI intensity in the cities of Noida, Ahmedabad, Vishakhapatnam and Bangalore, respectively, for longer duration of time that are in

Table 3. *UHII and its definition.*

Location and Paper	Year of UHI study	UHII (°C)	Method of calculation of UHI
Delhi Ahmad *et al.* (2011)	2006	9	Average of the maximum, minimum land surface temperature in the centre of the city and surrounding rural areas along four different profiles
Delhi Pandey *et al.* (2012)	2007–2010	4–7	Surface temperature of Delhi is compared to the surrounding rural areas for two months of a few consecutive years
Delhi Mohan *et al.* (2012)	2008	8.3	Difference between highest temperature and lowest temperature observed among all micrometeorological stations across the study area for a particular time (day)
Delhi Aslam *et al.* (2017)	2013	2.2	The simple temperature gradient between the urban areas to its surrounding rural areas for the given months
Kochi Thomas *et al.* (2014)	2011–2013	4.6	Near surface air temperature between urban and adjoining rural areas
Ernakulam Baby and Arya (2016)	2015	6	Change in peak temperature of a day between urban and semi-urban areas
Chennai Amirtham (2016)	2008–2009	4.1	Air temperature difference between urban and rural areas for different times of the day and in different seasons
Guwahati Borbora and Das (2014)	2009, 2013	2.12	Temperature differences in half hourly data recording in the day and night between highly urbanized and rural areas of the city
Bangalore Ambinakudige (2011)	2000, 2003	1–7	Difference in the mean temperature in the city core and the outgrowth zone
Visakhapatnam Devi (2006)	2006	2–4	The surface temperatures were plotted on a map of city and isotherms were drawn to compare the warm core at the centre and surroundings
Ahmedabad Goswami *et al.* (2016)	2003–2014	1.93	Land surface temperature difference at area of interest (city) with a buffer zone of 10 km adjoining the area of interest
Bathinda Sharma and Pandey (2015)	2015	2–5	Surface temperature difference between selected urban and rural areas

years. But in some studies, the UHI intensity is estimated for a few months (Deosthali 2000; Pandey *et al.* 2012; Borbora and Das 2014; Sharma and Pandey 2015; Amirtham 2016; Baby and Arya 2016; Aslam *et al.* 2017; Shastri *et al.* 2017). The temperature isopleths at different times of a day and night is analyzed by Amirtham (2016) for urban as well as rural locations in and around Chennai Metropolitan Area to derive UHI intensity. In Pandey *et al.* (2012) paper, surface temperature in central parts of Delhi is compared with the surrounding rural areas for the months of November and December for years 2007, 2008, 2009 and 2010 to identify the formation of day time cool island and nocturnal urban heat island over Delhi. UHI intensity was also calculated for a few days as in the works of Ambinakudige (2011), Mohan *et al.* (2012, 2013), Grover and Singh (2015) and for even a single day as done by Ahmad *et al.* (2011), Kannamma and Sundaram (2015), Kumar *et al.* (2017a) and Mehrotra (2018).

Using the Landsat 5 TM, the built-up and vegetated areas temperature for Delhi on 5 May 2010 and for Mumbai on 17 April 2010 is analyzed by Grover and Singh (2015) for finding the presence of surface UHI. The maximum and minimum land surface temperature during day and night time in Delhi, Aligarh, Agra and surrounding rural areas are captured using MODIS LST product for 26th June 2006 by Ahmad *et al.* (2011) to evaluate UHII. In Mehrotra (2018) paper, Landsat 8 images are used to study LST pattern over Mumbai city for 20th October 2016.

Pandey *et al.* (2012) have done UHI studies based on SHI, by comparing the temperature of central city of Delhi to its surrounding rural areas. The method of study is by using the thermal mapping with MODIS satellite data for the months of November and December 2017–2010. Both day and night temperatures are measured which help to reveal heat islands as well as cool islands in the city. It was found that a maximum of 4−6°C cool island and maximum of 4−7°C heat islands are formed in the central parts of Delhi. Another study by Mohan *et al.* (2012) was also based on the national capital region where the seasonal and annual temperature trends were studied for mean, minimum and maximum temperatures for the past few decades using the data from meteorological stations.

Thomas *et al.* (2014) have tried measuring near surface air temperature using 12 mobile surveys for a duration from January 2011 to March 2013. It was observed that UHI is intense in winter than in summer in Kochi, Kerala. During winter, the heat intensity reached up to 4.6°C in pre-dawn and 3.7°C in the early night. A HOBO data logger (HOBO U10 Temp/RH), enclosed within a white perforated plastic box is deployed for measuring air temperature and relative humidity in the studies of Amirtham (2016). The UHI intensity was computed with the reference data available from Meteorological stations and they found that the maximum daytime temperatures were based on the urban morphology and the time at which the measurement location is exposed to incident solar radiation. In Chennai Metropolitan Area (CMA), existence of a cool island with a temperature difference of 10.4°C in summer and 3.7°C in winter was found at the urban core during daytime. At the same time, the night-time UHI was ranging from 3.6°C in summer to 4.1°C in winter.

Borbora and Das (2014) have studied the temperature variation in two sites in urban core and two sites away from the Guwahati city. Stationary loggers were used to conduct *in-situ* measurements for the period of May to October 2009 and from June to August 2013 using mobile measurements. The UHI found was 2°C and the day-time UHI intensity has reached up to 2.12°C and night-time UHI intensity up to 2.29°C for the entire period of study.

Joshi *et al.* (2015) estimated the surface heat islands for winter and summer season of 2013 for Ahmedabad city using Landsat satellite data and field data. The field data was collected from 50 selected points in the city and the building temperature was measured using Infrared Gun. From the studies, the UHI effect was found more in the Gujarat Industrial Development Corporation (GIDC) Naroda and the maximum temperature ranges between 35° and 46°C. In similar way, remote sensing and field surveys are only used by Singh *et al.* (2017) to find out the land surface temperature for Lucknow city of Uttar Pradesh. The period of study considered here was the difference in LST in the year 2002 and 2014 and it was calculated using Landsat satellite data. The results showed that the temperature in the central portion of Lucknow city has been increased from 2002 to 2014 and vegetation cover was fallen down during this period. According to them, remote sensing is an ideal method for analyzing UHI but the disadvantage is that it is hard to study the microlevel change in temperature as well as for the selection of pictures of same land surface and atmospheric conditions.

Surface temperature as well as air temperatures were calculated by Chakraborty *et al.* (2016) to identify the heat island formation in the Kanpur city of Uttar Pradesh. In the study, air temperature was measured using sensors and the surface temperature was derived from outgoing longwave radiative flux. Land surface temperature pattern were also estimated using MODIS TERRA satellite data system. SHI and CHI are evaluated using difference in surface temperatures and air temperatures, respectively. A recent study conducted in 2018 by Ali Gazi and Mondal (2018) for Kolkata Metropolitan Area is again using Landsat Satellite data. The UHI was identified based on LST for the last 17 yrs from 2000 to 2017 and the results show an increase in the trend of mean temperature of the area.

4. Methods of UHI study

Various methods have been developed to study UHI in different parts of the world. Ever since the start of identifying the importance of UHI study, theoretical/empirical based studies are available. But for a real time estimation of the presence of UHI and to find the ways of mitigating its effects, the methods used are observational, experimental and computational studies (Mirzaei *et al.* 2010).

Observational approaches include remote sensing, field measurements and meteorological weather station data (Sahu *et al.* 2014). Table 4 shows the methods employed in the UHI studies in Indian cities.

4.1 *Satellite data*

From table 4, it is found that more than 60% of the studies were done with the help of remote sensing by finding the LST data (Ambinakudige 2011; Ahmad *et al.* 2011; Nesarikar-Patki and Raykar-Alange 2012; Babazadeh and Kumar 2015; Grover and Singh 2015; Kikon *et al.* 2016; Kumar and Singh 2016). The variants of LANDSAT satellite is majorly used to get land surface images for the UHI study. Commonly used LANDSAT versions and

Table 4. *UHI – method of study.*

Sl. no.	Paper	Variable	Method of study
1	Kikon *et al.* (2016)	LST	Satellite Data
2	Mohan *et al.* (2013)	LST	Satellite Data, Fixed station data
3	Babazadeh and Kumar (2015)	LST	Satellite Data
4	Kumar *et al.* (2017a)	LST	Instrumental Measurement
5	Ambinakudige (2011)	LST	Satellite Data
6	Gopalakrishnan *et al.* (2003)	AT, ST	Mesoscale Models
7	Devi (2006)	ST	Field survey
8	Gupta *et al.* (2009)	ST	Satellite Data
9	Gupta (2012)	ST	Satellite Data
10	Deosthali (2000)	AT	Mobile survey
11	Ahmad *et al.* (2011)	LST	Satellite Data
12	Grover and Singh (2015)	LST	Satellite Data
13	Ramachandra and Kumar (2010)	AT, LST	Satellite Data
14	Goswami *et al.* (2016)	ST	Satellite Data
15	Swain *et al.* (2016)	LST	Satellite Data
16	Kannamma and Sundaram (2015)	PET	Instrumental Measurement
17	Mehrotra (2018)	ST	Satellite Data
18	Kumar *et al.* (2017b)	LST	Satellite Data
19	Pandey *et al.* (2012)	ST	Satellite Data
20	Baby and Arya (2016)	AT	Instrumental Measurement
21	Mohan *et al.* (2011)	AT	Fixed station data
22	Borbora and Das (2014)	AT	Instrumental Measurement
23	Aslam *et al.* (2017)	AT	Satellite Data, Fixed station data, Mesoscale model
24	Thomas *et al.* (2014)	AT	Mobile survey, Fixed recording station
25	Mohan *et al.* (2012)	LST, AT	Satellite Data, Field survey, Fixed station data
26	Shastri *et al.* (2017)	LST	Satellite Data
27	Sharma and Pandey (2015)	ST	Instrumental Measurement
28	Nesarikar-Patki and Raykar-Alange (2012)	LST	Satellite Data
29	Kumar and Singh (2016)	LST	Satellite Data
30	Amirtham (2016)	AT	Fixed station data
31	Singh *et al.* (2017)	LST	Satellite Data
32	Joshi *et al.* (2015)	ST	Satellite Data, Field Data
33	Ali Gazi and Mondal (2018)	LST	Satellite Data
34	Chakraborty *et al.* (2016)	ST, AT	Fixed station data, Mobile survey Satellite Data

the sensors used in the collected papers are listed in table 5. These satellites are equipped with sensors such as MODIS, TERRA, TIRS, TM, ETM, ASTER, AVHRR, etc. The expansion of each term is listed down in table 6.

The above given list of satellites and sensors are utilized for the extraction of LST. Remote sensing is employed in finding the land surface temperature, because satellites and the earth is always in motion and capturing the moving air temperature above the ground is a risky task from the point of accuracy.

The available satellite thermal sensors give the temperature data at different spatial resolutions. The spatial resolution varies from kilometers to meters. Commonly used satellites/sensors for the heat island study and their resolutions are given in table 7.

4.2 *Fixed weather station data*

Meteorological weather station data is another means of finding the temperature in the urban and rural areas. In papers of Mohan *et al.* (2011, 2012, 2013), Amirtham (2016), Aslam *et al.* (2017), weather station data is used to analyse temperature in the city, especially for estimating AHI intensity. Mohan *et al.* (2013) utilized micro-meteorological measurements to derive land surface temperatures over 28 locations of Delhi metropolitan city. According to Mohan *et al.* (2013), fixed weather stations usually provide

Table 5. *Remote Sensing used for UHI study.*

Sl. no.	Paper	Variable	Remote Sensing (Satellite Data)
1	Kikon *et al.* (2016)	LST	LANDSAT ETM, LANDSAT -8
2	Mohan *et al.* (2013)	LST	MODIS
3	Babazadeh and Kumar (2015)	LST	LANDSAT 7 & 8
4	Ambinakudige (2011)	LST	LANDSAT ETM+
5	Gupta *et al.* (2009)	ST	NOAA, LANDSAT ETM+, AVHRR
6	Gupta (2012)	ST	TERRA/MODIS
7	Ahmad *et al.* (2011)	LST	MODIS
8	Grover and Singh (2015)	LST	LANDSAT 5TM
9	Ramachandra and Kumar (2010)	AT, LST	LANDSAT MSS, LANDSAT TM, LANDSAT ETM+, IRS, LISS-111
10	Goswami *et al.* (2016)	ST	MODIS
11	Swain *et al.* (2016)	LST	MODIS, LANDSAT-5, LANDSAT-7
12	Mehrotra (2018)	ST	LANDSAT 8 OLI/TIRS
13	Kumar *et al.* (2017b)	LST	MODIS
14	Pandey *et al.* (2012)	ST	MODIS
15	Aslam *et al.* (2017)	AT	MODIS
16	Mohan *et al.* (2012)	AT, LST	MODIS-TERRA
17	Shastri *et al.* (2017)	LST	MODIS
18	Nesarikar-Patki and Raykar-Alange (2012)	LST	IDRISI-Andes, LANDSAT
19	Borbora and Das (2014)	LST	LANDSAT TM, LANDSAT ETM+
20	Singh *et al.* (2017)	LST	LANDSAT TM, LANDSAT 8
21	Joshi *et al.* (2015)	ST	LANDSAT ETM, LANDSAT 5
22	Ali Gazi and Mondal (2018)	LST	LANDSAT 5 TM, LANDSAT 7 ETM+, 8 OLI
23	Chakraborty *et al.* (2016)	ST, AT	MODIS TERRA

Table 6. *Expansion of the terms.*

Abbreviation	Expansion
GOES	Geostationary Operational Environmental Satellite
NOAA	National Oceanic and Atmospheric Administration
AVHRR	Advanced Very High Resolution Radiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
TM	Thematic Mapper
ETM	Enhanced Thematic Mapper
MSS	MultiSpectral Scanner
OLI	Optical Land Imager
TIRS	Thermal Infrared Sensor

better temporal resolution of data. Information from four meteorological stations one each at Rohtak, Gurgaon, Palam and Safdarjung are utilized for annual and seasonal mean minimum temperatures in the national capital region of India (Mohan *et al.* 2011). In another study by Aslam *et al.* (2017), meteorological data from the two stations in Delhi is collected to assess the seasonal variation of UHI as well as air-quality. Mega city Delhi is analyzed by another group (Mohan *et al.* 2012) using three weather stations data and compared it with the field campaign and remote sensing information. In order to compute heat intensity in Chennai metropolitan area, the reference data from Nungambakkam meteorological station were utilized by Amirtham (2016).

4.3 *Field survey*

Field measurements can be of two types: Stationary survey (Mohan *et al.* 2012; Thomas *et al.* 2014) and mobile survey (Deosthali 2000; Thomas *et al.* 2014). In stationary survey, a fixed location will be chosen and measures the temperature variation over there using the instruments like thermometers (figure 2). For mobile survey, usually selected routes of different land use types are travelled by a vehicle in which the temperature measuring instruments are already attached. Commonly used instruments to measure heat intensity are Infrared thermometer, Psychrometer, Digital thermometer, RTD probe, Automatic temperature recorders, Max tech Digital thermometer, etc. (table 8).

Table 7. *Satellite versions and its resolution.*

Sl. no.	Satellite/Sensor	Resolution (m)
1	LANDSAT MSS	60
2	LANDSAT TM	30
3	LANDSAT ETM+	30
4	LANDSAT 4/TM	120
5	LANDSAT 5/TM	120
6	LANDSAT 7/ETM+	60
7	LANDSAT 8/TIR	100
8	GOES	4 km
9	NOAA-AVHRR	1 km
10	EOS-1 (Terra)/MODIS	1 km
11	EOS-1 (Terra)/ASTER	90

Infrared thermometer, used by Kannamma and Sundaram (2015) and Kumar *et al.* (2017a), studies on the principle of converting infrared energy focused on a detector to electrical signals and displays the corresponding temperature after manipulation. The details of the instruments used for finding heat island intensity is given in the paper by Sahu *et al.* (2014).

Like infrared thermometers, digital thermometers are also used to measure temperature (Sharma and Pandey 2015; Baby and Arya 2016). It consists of different types of sensors and the sensor types used are thermocouple, thermistor and resistance temperature detector (RTD). Temperature data loggers usually store temperature measurements over a defined period of time automatically. HOBO data logger, used by Amirtham (2016), consists of integrated sensors for temperature and humidity measurements of outside environment. In HOBO Pro V2 (Borbora and Das 2014), there are weatherproof temperature and humidity data logger with external sensors. Another data logger, called Thermohygro data loggers are used by the The Energy and Resources Institute team (Sastry *et al.* 2013) to conduct field measurement for

(a) Infrared thermometer **(b)** Psychrometer

Figure 2. Instruments used in field survey to measure UHI intensity (from Google images).

Table 8. *Instruments used in UHI study.*

Sl. no.	Paper	Variable	Instruments
1	Kumar *et al.* (2017a)	LST	Infrared thermometer
2	Deosthali (2000)	AT	Psychrometer
3	Kannamma and Sundaram (2015)	PET	Infrared thermometer
4	Baby and Arya (2016)	AT	Digital thermometer
5	Borbora and Das (2014)	AT	HOBO Pro V2, RH Data loggers
6	Thomas *et al.* (2014)	AT	RTD probe, Automatic temperature recorders
7	Sharma and Pandey (2015)	ST	Max tech Digital thermometer
8	Amirtham (2016)	AT	HOBO Data logger

analysing the air temperature at different land use types within Bangalore city.

4.4 *Numerical modelling*

Indian studies are in its preliminary stage in the approach of numerically modelling and analysing the heat island formation in the urban area. This requires proper inputs and high computational facilities. According to the spatial scale, the models are classified as mesoscale and microscale models. In general, a climatic system is an interactive and interdependent system of atmosphere, ocean, land surface, snow and ice. So a general circulation model (GCM) or global climate model is a mathematical model in planetary scale with grid resolution of the order of 100 to 200 km and consists of basic fluid flow equations that are derived from physical laws in order to simulate the interactions between the atmosphere, ocean, land surface and ice systems. Individual models such as atmospheric model consists of governing equations of atmospheric motions and oceanic model consists of physical and thermodynamic processes in oceans as well as coupled atmospheric and oceanic GCMs called atmosphere–ocean coupled general circulation model is also available. Some developed models are global forecast system (GFS), intermediate general circulation model (IGCM), Varsha GCM, Hadley Centre Coupled Model, version 3 (HadCM3), educational global climate model (EdGCM), etc.

Another subcategory is that the regional climatic models (RCMs) which are the mesoscale models that concentrate on the climatic state over a region or of smaller spatial scale than GCM or a limited area of interest. The large scale processes are considered as boundary conditions for every 3 or 6 hrs to the regional scale model to simulate the climate over a region. One of the most widely used RCM is the Weather Research and Forecasting model, WRF (Aslam *et al.* 2017). But the local climatic processes cannot be modelled using the mesoscale models. The local climatic changes occur due to the topography of that particular area and many RCMs are not capable to account for these due to coarser spatial resolution. That is, the spatial grid size is larger than the area that covers the effect of localized climatic phenomenon. In such cases a climatic study over a city can be done through microscale models which are having finer grid resolution when compared to mesoscale models.

Significant growth in the development of microclimatic models are occurring since the urbanization impacts are confined to very limited area and climate modelling in the city scale is a much complex task. For these reasons researchers started making use of computational fluid dynamics (CFD) models for simulating the city scale region. CFD is a platform which interconnects mathematics, physics and computation using softwares and are widely used in all scientific and technical fields. There are group of researchers who conduct studies on high-resolution large eddy simulation (LES) models for climate study. In his paper, Marques Filho *et al.* (2013) analyzed the vertical structure of UHI in the tropical region using LES models. The results show that LES can capture the mesoscale circulation pattern formed due to the surface heterogeneity. Similarly, in another paper Zhang *et al.* (2013) used the LES of WRF model for simulating the planetary boundary layer features. This is also based on spatial heterogeneity in formation of mesoscale circulation pattern. The domains considered here are in the range of kilometers. When coming down to a scale of within one or two kilometers of domain size, CFD models are highly preferred.

The microscale climatic study using CFD is an emerging field of research globally, but in India CFD urban studies are very limited. In papers by Gopalakrishnan *et al.* (2003) and Aslam *et al.* (2017), mesoscale models are used to find the heat patches in south Indian cities and the capital city, respectively. Advanced Research WRF (ARW) model version 3.7 is used in the paper by Aslam *et al.* (2017) to evaluate diurnal variation of UHI, wind speed and ground heat flux during the months of May and December 2013. The influence of vegetative cover, water bodies and reflective materials in buildings on decreasing the hotspots in the city is analysed by the TERI team (Sastry *et al.* 2013) using field survey. The results obtained from field measurements are validated using software tools such as ENVI-met. A good correlation was found with the simulated data eventhough it is lower than the measured one.

5. Results and discussion

The main classification of UHI study methods are theoretical, observational, experimental and numerical methods. Mills (2014) classified the approaches to the study of urban climate effects in each time period. According to Mills (2014), during the year 1900, urban climate effects were observed using conventional meteorological equipments such as thermometers, hygrometers, etc. Then in 1960s, study moved towards measuring the climatic process variables like radiation, sensible and latent heat exchanges. Statistical methods were utilized for analysing the results. Conventional micro-meteorological theories were started in 1970s. This is the period when Oke (1973) formulated theories to study urban climates and heat islands. Moreover, computer modelling techniques were slowly initiated during this time. In 1980s, experimental methods were implemented. Small scale physical models of urban forms were made for direct measurement of fluxes. The relationship between real urban forms and real time climate effect were first analysed in 1990s. 21st century gave the breakthrough for urban climate study where development of realistic urban climate models was started. Application of numerical models including CFD came into role for identifying and studying the climate effects in cities. But when Indian climatic studies are concerned, it was initiated in 21st century only and the studies are more based on observational approaches and remote sensing data. The experimental setup of buildings into blocks and analysing the temperature along wind flow patterns are not seen in any of the studies. The research on employing numerical models to the field of climatology is also minimal. Only very few studies of the order of 7% of the total papers collected includes on numerical models.

Each method has its own advantages and limitations. Theoretically approaching the problem without having definitive profiles of all influencing variables such as temperature, wind velocity, moisture content is almost impossible (Oke 1968). So in general, empirical relations are derived using statistical relations between the important variables. Specification of these variables may in turn require inputs from other methods. Usually it is in the form of prediction of one variable according as a function of another one. This limits the applicability of these simple methods for solving realistic problems (Oke *et al.* 2017).

Observational approaches include weather station data, instrumental measurement for fixed locations and the mobile surveys. Field measurements were the initial way of UHI study first used by Luke (1818). Advanced instruments present today help to get temperature fluctuation, velocity of air, humidity, solar radiation, precipitation, atmospheric pressure, etc. (Sahu *et al.* 2014). However, instrumental measurement either has to compromise on spatial scale or on the temporal scale. The fixed station measurements give the temperature data at the fixed locations (which can be a highest population area or highly marked urban area) where the instruments are fixed permanently. With high resolution instruments, we can measure the temperature for a long time but spatially it is constrained to only a single location. When there is a need for larger spatial coverage more instruments are required and with a network of fixed stations which is again expensive.

Mobile measurements are another way of calculation with larger exposure to the spatial scale, then there the restriction is on the time duration. Because, here space is not fixed but the time of measurement at each location is different and it is not possible to have temperature recordings for whole duration of the day for every location. Another issue with mobile measurement is that if there is no way to account for the movement of sensor relative to the wind flow, then this method is not suitable for wind observations (Oke *et al.* 2017). Therefore, fixed as well as mobile surveys give data at limited locations and getting the information over a wide range area is time consuming and expensive. The number of variables simultaneously measured are also countable (Mirzaei *et al.* 2010). Thus, field surveying is not always possible in all the locations at all the time, instruments required to measure temperature and other dependent instruments are again costlier as well. Similarly, in the case of weather station data, the number of stations and information can be collected for a larger spatial area are also limited.

Experimental methods using physical models always approximate the shapes of buildings into blocks and the variation of only a few variables can be analysed. Remote sensing using the satellites is another method widely used in urban studies which can provide very accurate land surface features. But accuracy of the air temperature evaluation away from the surface is not up to the mark. That is, satellite observations can find the land surface and roof of buildings, but it cannot see variation away from the walls and predict the heights of urban structures. So other than land surface temperature, estimating air temperature at higher elevation from the ground cannot be easily predicted with remote sensing (Vogt *et al.* 1997; Benali *et al.* 2012). Using land surface temperature, estimation of air temperature at a height of

2 m above the ground which is very adjacent to the surface is possible. But the temperature evaluation within the cities of having high-rise buildings of height above 50 m cannot be predicted using satellite data. Since air is constantly moving on the land surface, predicting the air temperature spatially and temporally accurate is more difficult. Another factor is that satellite data is helpful when the horizontal land area in hundreds of meters or kilometers. But for a limited area of study in few metres the satellite data cannot be used unless the sensor resolution is very fine.

Numerical models are having better spatial resolution than the satellite data. The spatial scale varies from kilometers to metres. There are mesoscale (large scale of the order of 100s of kilometers) and microscale models (small scale of the order of a few meters) are available now (Mirzaei *et al.* 2010). One of the indigenous speciality of these models is that this approach helps for predicting the future climate as well. The limitation comes at the validation of these models. It is still in its developmental stage. Without the models are validated with real data, the models cannot be used for urban climate study (Oke 2006). If validated properly, the urban models help a lot in the practical section of planning and changing policies when the knowledge is transferred to the concerned group.

Nowadays, CFD studies are gaining popularity globally due to the fact that they can achieve high spatial resolution compared to other numerical models like mesoscale meteorological model as well as remote sensing data. According to Toparlar *et al.* (2017), there is a trend of rapid increase in CFD studies of urban microclimate in recent years. They reviewed a total of 183 studies, the earliest study from 1998 to the latest from 2015. As per Toparlar *et al.* (2017), last three years (2013−2015) constitute more than half of all the studies (104 of 183 studies). Toparlar *et al.* (2017) review wide range of possibilities of CFD in urban climate study. According to them (Toparlar *et al.* 2017), to improve predictive capability of CFD simulations the validation of models with measurement data is required in future studies. When the status of Indian climate research is considered, use of CFD in urban climate modelling is in its very preliminary stage. While numerical models are extensively used for pollution dispersion, wind effects and other microclimatic studies, the published studies are not available for the use of CFD models to find temperature distribution in the cities of India.

6. Conclusion

In Indian climate studies, satellite data is used more to evaluate urban heat island in the urban and rural areas. Other methods are field measurements, which include instrumental measurements (through mobile surveys and fixed locations) and by accessing weather station data. Numerical modelling is one of the best way to evaluate heat islands and to predict the future climate of the cities. Globally, application of CFD in urban microclimate studies is a trending field of research of 21st century but even now India stands in its preliminary stage. Mesoscale models and CFD models are used for finding pollutant dispersion in the cities, but published studies on heat island studies using numerical models are very rare.

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