Seasonality of Surface Urban Heat Island in Delhi City Region Measured by Local Climate Zones and Conventional Indicators

Bakul Budhiraja, Lech Gawuc, and Girish Agrawal

***Abstract*—Urbanization can change the local climate of an area, one manifestation of which is a rise in the local temperature of built-up areas, a phenomenon known as an urban heat island. The thermal response of built-up areas in comparison to natural areas is quantified in terms of surface urban heat island (SUHI) intensity. The work presented here evaluates the seasonal SUHI intensities in Delhi using local climate zones (LCZs) and conventional SUHI indicators in parallel. Statistical analyses are carried out to determine the relationship between them and to delineate heat stressed zones in the Delhi city region. The present study is the first one that utilizes LCZs for seasonal SUHI analysis in Delhi. The land surface temperature (LST) is assessed using a hundred and five night-time images from MODIS. Unambiguous night-time SUHI effect is seen for all seasons. The maximum night-time SUHI intensity is 3.5° C, between "compact low-rise" (LCZ 3) and "low plants" (LCZ D) in summer and winter. The conventional indicator "Inside urban-Inside rural" gives the highest night-time SUHI intensity of 3.3° C, in autumn. Statistical analyses show that "compact low-rise" (LCZ3) and "large low-rise" (LCZ8) are the most heat-stressed LCZs. The largest number of distinct thermal zones is created in the monsoon, followed by summer and winter. The results suggest that in order to minimize the UHI effect, further urban expansion in the Delhi region should be restricted to LCZ 5 (open mid-rise) and LCZ 6 (open low-rise).**

***Index Terms*—Delhi city region, land surface temperature (LST), local climate zones (LCZs), seasonality, SUHI indicators, surface urban heat island (SUHI).**

I. Introduction

THE replacement of natural surfaces by artificial building materials modifies the aerodynamic, radiative, thermal, and moisture properties of the local area. The manner in which these alterations cause a change in the energy and water balance regimes is not fully understood [1], [2]. The difference in temperature between urban and rural areas is termed as the urban heat island (UHI) effect. This is a direct consequence of the alterations in the surface energy balance (SEB) of the area [3]. Depending on the type of temperature and the observational methods, different types of UHIs are defined. Whereas, UHI is the term most commonly used when talking about urban–rural temperature differences, it is more appropriate to restrict its usage to near-surface air temperature differences. "Surface UHI" (SUHI), proposed by Voogt and Oke [4], is better suited when discussing the difference between urban and rural land surface temperature (LST).

LST is of prime importance in any study of urban climate because it directly modulates the lower layers of the planetary boundary layer, and indirectly, the free atmosphere. LST plays a significant role in the SEB. A number of studies have explored the relationship of remotely sensed LST with various aspects of urban climate such as urban SEB [5], nonurban SEB [6], urban surface temperature [7], urban land cover [8], characteristics of population [9], spatial growth of cities [10], spatial resolution and SUHI [11], and surface imperviousness [12].

Satellite technology provides spatially continuous observations of LST over large areas. The urban configurations of Delhi vary spatially, and given the region's rapid spatial growth and increasing population density, it is critical to understand the local-climate, including SUHI phenomenon. As discussed below, due to the lack of any dense, *in-situ* observational networks in the Delhi region, most studies have employed remotely sensed LST. An unfortunately large number of urban climate studies provide insufficient information about the methodologies employed, reducing the usefulness of such studies [13]. Some of the problems are an incomplete or inappropriate description of urban forms, lack of information about instrument siting, and incomplete information or erroneous delineation of the boundaries between urban and rural areas.

Mallick *et al.* [14] used two night-time ASTER images, to obtain an SUHI intensity of 4° C in October, attributed to the difference between central business districts/industrial areas and suburbs. A SUHI intensity of 3° C between urban and vegetation was reported by Kant *et al.* [15] in the transition month of October using ASTER imagery. Annual heat stress areas—maximum intensity of 16.7° C in summer, and 7.4° C in winter—were identified by Sharma and Joshi [16] using an anomaly study based on five Landsat TM5 images. Singh *et al.* [17], using five Landsat TM5 scenes, claimed a weak daytime SUHI in

Manuscript received January 9, 2019; revised July 24, 2019 and October 17, 2019; accepted November 11, 2019. Date of publication January 31, 2020; date of current version February 4, 2020. The work of L.Gawuc was supported by National Science Centre (Poland) under Grant "Preludium" 2016/21/N/ST10/00430. The work of B. Budhiraja was provided by Shiv Nadar University. The work of G. Agrawal was provided by Shiv Nadar University and O. P. Jindal Global University. *(Corresponding author: Bakul Budhiraja.)*

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Digital Object Identifier 10.1109/JSTARS.2019.2955133

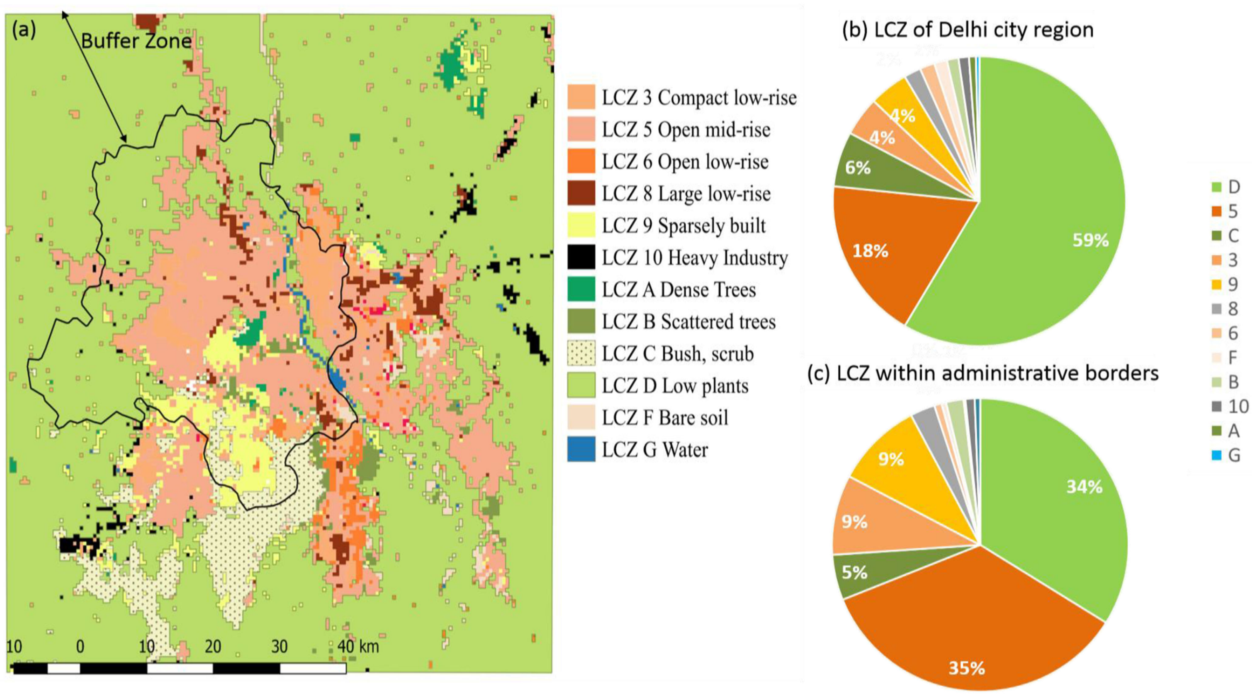

Fig. 1. (a) LCZs in the city region of Delhi (Source—WUDAPT). (b) Area of each LCZ in Delhi city region. (c) Area of each LCZ in Delhi administrative borders.

the core of Delhi—one for each season. Mohan *et al.* [18] studied SUHI in Delhi using MODIS and micrometeorological station data for four days in one summer. The maximum SUHI intensity reported was 8.3° C between the dense canopy and green area. Pandey *et al.* [19], using the MODIS LST monthly composite (MOD11C3.005) for the period 2000–2012, reported a maximum SUHI intensity of nocturnal heat island in March of 4–6° C and a minimum of 0–2° C in the monsoon months between the urban core and rural periphery.

The conventional system of SUHI indicators to estimate SUHI intensity has a high dependency on the administrative/political boundaries of cities to define "urban." Such delineation introduces many uncertainties in the estimated intensity. For example, Liu *et al.* [20] used 60% land imperviousness as an urban–rural border for Beijing. Most of the European SUHI studies use administrative boundaries as a reference distinction between city and countryside [21], [22], [23]. Additionally, existing UHI studies of Delhi [14], [15], [16], and [18] use political boundaries to calculate UHI intensity. Only the study by Pandey *et al.* [19] looks at the UHI phenomenon for Delhi in a regional context. The administrative boundaries rarely correspond to land use and land cover (LU/LC) change, hampering the interpretative potential of SUHI studies. Moreover, the manner in which city borders are specified varies across countries, regions, or even single cities. Delhi is a good example of such a city, where administrative borders are not suitable to distinguish "urban" from "rural" (see Fig. 1). This study analyzes SUHI in a city-regional context using "urban forms" based on LCZs.

Comprehensive classification schemes for urban forms might be useful in overcoming some of the problems in differentiating between urban and rural. Since cities around the world differ significantly in their morphology and activity of inhabitants, comparing UHI or SUHI studies across various cities is a challenge. To address some of the difficulties with a description of city forms, Stewart and Oke [24] proposed a classification, called "local climate zones" (LCZs). The scheme aims to provide a universally applicable thermal climate-based classification of urban and rural sites. LCZs are defined as "regions of uniform surface cover, structure, material, and human activity that span hundreds of meters to several kilometers in horizontal scale" [24]. LCZ mapping decomposes cities into distinct urban landscapes based on a range of physical parameters that generates similar thermal signatures at the neighborhood scale.

LCZs are intended to provide objective measurements of UHI magnitude worldwide. The World Urban Database and Access Portal Tools (WUDAPT) is a community initiative to collect worldwide data on the urban form, i.e., morphology and materials, and function, in other words, use and metabolism. WUDAPT provides a comprehensive and consistent LCZ database for many cities [25]. The LCZ scheme has been widely adopted for urban climate studies [26]. Improving the delineation of LCZs is an active research area [40], [41]. For this study, the LCZ classification method provided by WUDAPT is used for the region of the city of Delhi, including the "satellite" cities.

Table I shows the results of the differences in mean LST observed for a range of LCZs in various cities. Nassar *et al.* [27] studied surface urban heat sinks and islands in Dubai using MODIS and Landsat 8 imagery. Nocturnal SUHI of 3.5° C was observed in winters with "compact mid-rise" exhibiting the strongest warming effect. Gelectic *et al.* [28] used Landsat 8 and ASTER images for Prague and Brno within the Czech Republic. "Heavy industry" (LCZ 10), "compact low-rise" (LCZ 3), and

TABLE I
SUHI INTENSITIES REPORTED USING LCZ APPROACH

City	Population (millions)	Köppen climate zone	Data & Method	SUHI key results
Prague [28]	1.3	Cfb	Landsat & ASTER (N & D)	LCZ 10, 3 & 2 warmest, LCZ G & A coolest
Dubai [27]	2.5	Bwh	MODIS & Landsat 8 (N & D)	LCZ 2-F = 3.5°C
Hangzhou [29]		Cfa	ASTER (N)	LCZ 1-A = 4.2°C
Fuzhou [30]	3.3	Cfa	Landsat (D)	LCZ 2-D = 6.73°C
Delhi [Current Study]	25	Cwa & BSh	MODIS (N)	LCZ 3-D = 3.5°C

Cfb: Marine West Coast, Cfa: Humid subtropical.
Cwa: Humid subtropical.
BSh: Semiarid, Bwh: Tropical and subtropical desert.
D: daytime and N: night-time.

"compact mid-rise" (LCZ 2) were identified as warmest in both cities. Cai *et al.* [29] studied the Yangtze River delta, a heavily urbanized area around Shanghai using ASTER along with Landsat 8 data. "Compact high-rise" (LCZ 1) was reported to be the warmest, and "low-plants" (LCZ D) as the coolest. "Water surfaces" (LCZ G) had the highest LST in the night.

Before Stewart [13] proposed the LCZ scheme, most SUHI studies were based on "urban–rural" or indicators based on administrative borders (Schwarz *et al.* [21]). Stewart *et al.* [24], [26] remarked that the differences of temperature observed for LCZs might be applied as a definition of UHI intensity. In recent years, there has been a proliferation of research papers, which utilize LCZ for UHI or SUHI analysis. The primary objective of the research presented here is to evaluate the seasonal behavior of SUHI of the city-region of Delhi. The SUHI is analyzed using two approaches, LCZs and conventional SUHI indicators. Using the two approaches in parallel also helps in understanding the relationship between the "urban" and its physical characteristics, i.e., its "urban forms," through Pearson correlation analysis. The dataset analyzed comprises 105 night-time MODIS satellite images (MOD/MYD11A1 product). The Analysis of variance (ANOVA) test is used to see if statistically significant thermal zones are created. The Tukey test is used to identify seasons with more distinct LCZs, as well as to help identify heat-intensive LCZs.

II. Materials and Methods

A. Study Area

The megacity of Delhi, officially referred to as the National Capital Region (NCR) of Delhi, lies in Northern India at 28.7041° N, 77.1025° E. It covers an area of 1483 km^2 with a total population of 29 million as of 2018 [31]. The megacity is projected to continue growing and become the most populous city by 2030 as per the latest Revision of World Urbanization Prospects (2018). Delhi has expanded beyond its administrative borders, the black line in Fig. 1, with many satellite cities, which are included in the NCR of Delhi. The climate of the city is an overlap between monsoon-influenced humid subtropical and semiarid. Delhi experiences five seasons, namely, winter, spring, summer, monsoon, and autumn. The air temperature ranges from a maximum of 43–46° C in the summer months of April, May, and June, to a minimum of 2–4° C in December and January. The average annual air temperature is 25.2° C and mean annual rainfall is 693 mm. The two most prominent features of the geography of Delhi are the Yamuna flood plains and the Delhi Ridge. The Ridge originates from the Aravalli Range in the south and encircles the west and north-west parts of the city. Delhi is prone to heat waves and has poor air quality [32], [33]. The megacity has close to 1.8 million people living in slums [34], with no capacity to equip themselves for increasing heat stress.

TABLE II
SEASONAL AVAILABILITY OF MODIS SATELLITE DATA

Season	Day of year (DOY)	Number of scenes
Spring	32-90	12
Summer	91-181	40
Monsoon	181-259	21
Autumn	260-334	21
Winter	335-365 0-31	11
Annual	0-365	105

B. Data

The LST is retrieved using MODIS night-time images. The Terra and Aqua MODIS products furnished 105 nocturnal satellite images for 2015 (see Table II). The standard MODIS MOD/MYD11A1 products are used. The MODIS Terra and Aqua images are selected based on the off-nadir angle (>30°), pixel availability, cloudiness, and data quality.

C. Local Climatic Zones

As a universal approach, Bechtel *et al.* [25], [35] described the procedure for delineating LCZ using Google Earth to train areas on Landsat 8 scenes, followed by random forest classification in SAGA-GIS environment. For the present study, the LCZs for the Delhi city region (see Fig. 1) are delineated using these procedures through the WUDAPT portal [36].

The LCZs found in Delhi city region are shown in Fig. 1. Part (a) of the figure shows the expansion of the urban agglomeration beyond Delhi's administrative borders, marked by the black line. The major LCZs found within the administrative borders [see Fig. 1(c)] are LCZ 5 (open mid-rise) and LCZ D (low plants), covering 34.9% and 33.8% of the area, respectively. The majority of Delhi city region, 58.7% of the area, is classified as LCZ D (low plants), with another 18.1% classified as LCZ 5 (open mid-rise). The areas classified as LCZ D are primarily agricultural land present around Delhi's urban agglomeration with a linear fringe present along the Yamuna River (LCZ G, water, covering 0.6% of the area) located near the eastern edge of Delhi. The areas classified as LCZ 5 (open mid-rise) are residential and commercial areas present in central Delhi and

TABLE III
SUHI INDICATORS BASED ON ADMINISTRATIVE BORDER

	Name	Brief Description
1	Urban*—outside rural	Difference between urban* LST and rural areas within a buffer around the city outside administrative borders
2	Inside urban—inside rural	Within city borders: mean LST of artificial areas—mean LST of (semi)natural areas
3	ISA core—urban*	Mean LST of areas with the highest imperviousness (>90%)—mean urban* LST
4	Urban*—water	Difference between mean urban* LST and mean LST of water surfaces
5	Urban*—forest	Mean urban* LST—mean LST of the area covered with dense forest
6	ISA core—forest	Mean LST of areas with the highest imperviousness (>90%)—mean LST of areas covered with dense forest
7	Urban*—agriculture	Mean urban* LST—mean LST of areas used for agriculture
8	Standard deviation	Standard deviation of urban* LST
9	Range	Maximum LST-minimum LST (within city borders)
10	Magnitude	Maximum LST within city borders—mean urban* LST

Star* indicates a mean LST calculated within administrative borders.

spreading outwards in all directions. LCZ 3 (8.8%) coexists with LCZ 5 (open mid-rise) prominently in East Delhi. LCZ 9 (sparsely built) occupies 9.5% of the area, and it is located in southern Delhi, which includes a large military cantonment area and residential areas located along the Aravalli mountain range, which itself is classified predominantly as LCZ C (bush and scrub), at 5% of Delhi's area. Patchy forest covers 2.9% of Delhi's area, mainly located on Pusa Hill forest in the Centre of the city, Kamala Nehru ridge toward north-east Delhi, and the Hauz Khas area in the southern part of the city. Most of the LCZ 8 (large low-rise) are concentrated in the northern and eastern fringes of the city. Industrial areas (LCZ 10) are located along the major highways in the NE and SW direction.

A LCZ is considered in this study only if it covers at least 0.2% of Delhi's area. Therefore, LCZ 1 (compact high-rise), LCZ 2 (compact mid-rise), LCZ 4 (open high-rise), and LCZ 7 (lightweight low-rise) are not considered.

D. Surface Urban Heat Indicators

Many of the previous SUHI studies use administrative borders [21], [37], [38], [39], as a source for classification. Such classification can lead to erroneous estimations of SUHI intensity for Asian cities because most of these cities generally do not conform to the typical European or North American city with a core urban center. The use of administrative boundaries makes comparison of SUHI intensity between different cities challenging. It has been shown that such indicators are inconsistent when single thermal observations [21], [22] or aggregated satellite composites [23] are utilized. Table III provides the list of indicators used, along with a brief description of each. Fuller descriptions are found in [21]–[23] and related papers. Note that for the purpose of the present study, some indicator names have been modified.

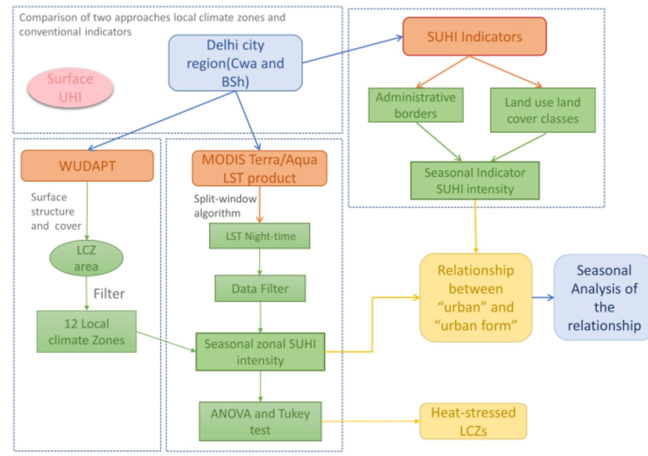

Fig. 2. Methodology chart.

The first seven indicators are based on LU/LC. Indicator 1 "Urban*-outside rural," which takes into account all nonurban areas located outside city borders. Indicator 7 "Urban*-agriculture" is based on croplands located outside city borders in the area of interest (AOI). The indicators from eight to ten are based on statistics calculated for LST within administrative borders.

The methodology followed for the current study has been shown (see Fig. 2). The seasonal analysis of SUHI for Delhi uses two approaches. The first is the conventional approach of SUHI indicators, which distinguishes "urban" using administrative borders and LU/LC. The second is the relatively recent LCZ approach, which contemplates "urban form" to understand the climatic variations in the thermal environment. The seasonal zonal intensity is statistically analyzed to delineate significant heat-stressed urban forms. In addition, the relationship between the "urban" and the physical composition of city in terms of "urban form" is analyzed.

III. RESULTS

A. Seasonal Behavior of SUHI

The seasonal differences of LST across LCZs are assessed by plotting the deviation of LCZ mean from the seasonal mean value for night-time (see Fig. 3).

The LCZs for areas with natural, pervious surfaces, i.e., A—dense trees, C—bush and scrub, D—low plants, F—bare soil, and 9—sparsely built, have LST skewed negatively from the mean. Whereas, LCZ numbers 3—compact low-rise, 5—open mid-rise, 6—open low-rise, and 8—large low-rise, which indicate built-up (urban) areas, are skewed positively from the mean, highlighting the high thermal capacity of urban materials. The high heat capacity of water (LCZ G) has been reported earlier [29], in that it remains warmer during the night compared to other natural LCZs. The range of average LST values in LCZs is $\pm 2^\circ$ C from the mean. The highest deviation from the mean is seen for LCZ D (low plants) and LCZ 3 (compact low-rise).

The SUHI phenomenon is distinctly observed at night during all seasons. The highest SUHI intensity of 3.5° C is observed between compact low-rise (LCZ 3) and low plants (LCZ D)

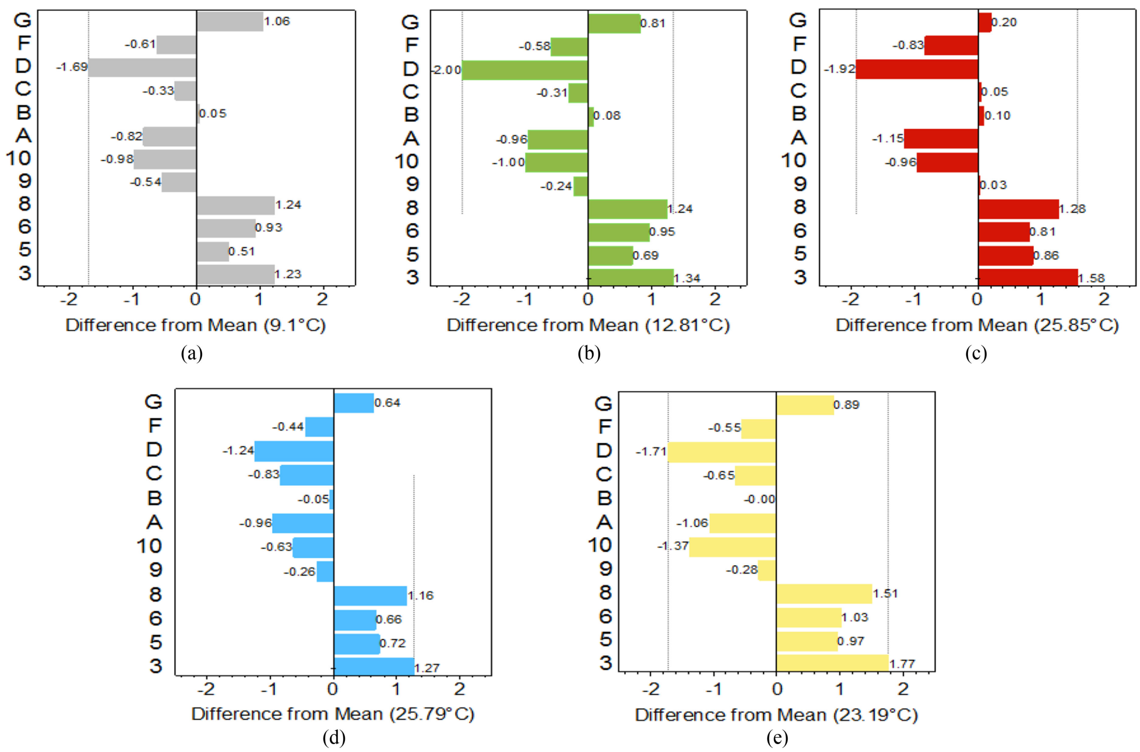

Fig. 3. Seasonal variation of SUHI intensity using indicators. (a) Winter. (b) Spring. (c) Summer. (d) Monsoon. (e) Autumn.

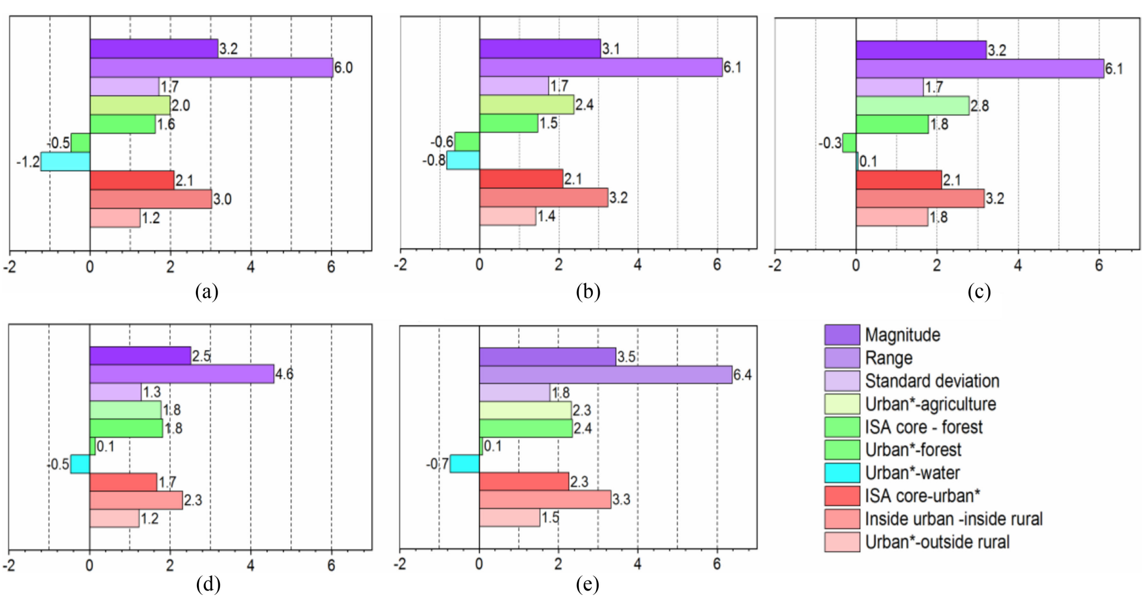

Fig. 4. Seasonal variation using LCZ, Star* indicates a mean LST calculated within administrative borders. (a) Winter. (b) Spring. (c) Summer. (d) Monsoon. (e) Autumn.

in summer (see Fig. 3). The warmest LCZ 3 (compact low-rise) produces an SUHI intensity of 3–3.2° C when compared to dense trees (LCZ A) and heavy industry (LCZ 10). The second highest SUHI intensity of 2.5–3.2° C is observed as a difference between large low-rise (LCZ 8) and low plants (LCZ D). Open mid-rise (LCZ 5), comprising the largest residential zone, remains 3° C warmer than low plants (LCZ D) or rural counterparts. Among the seasons, summer experiences the highest SUHI intensity, followed by autumn, spring, and winter. The lowest intensity is noted during the monsoon.

The SUHI intensity is significantly impacted by the definition of urban and the method used to calculate the urban LST, which is defined by the administrative boundaries (see Fig. 4). The seasonal variability in SUHI intensity is also understood using

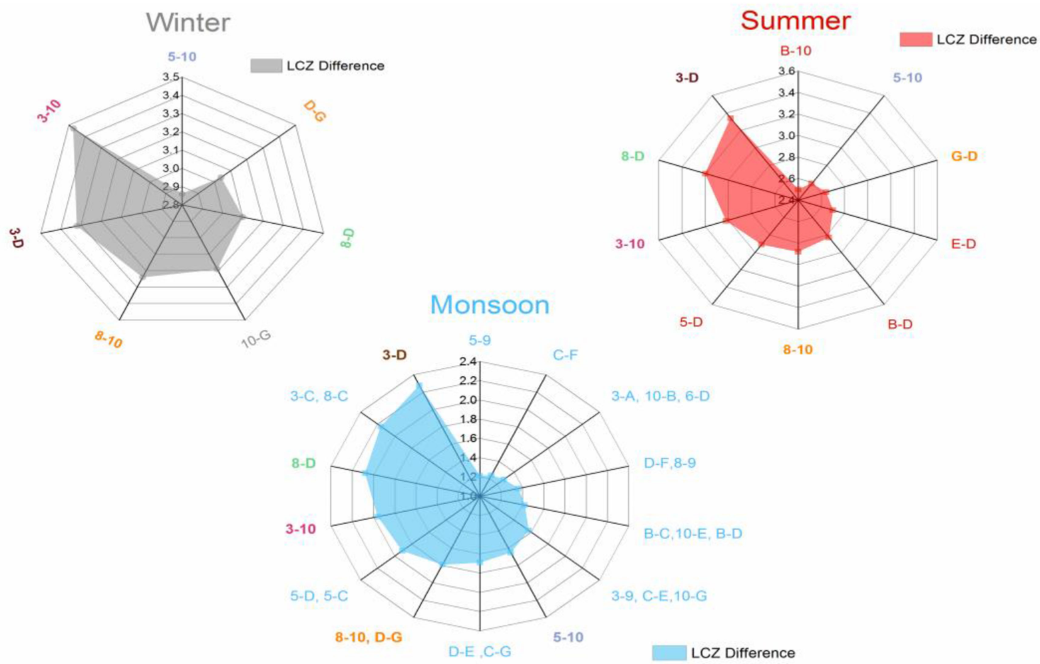

Fig. 5. LCZ pairs with significant differences in SUHI intensity.

TABLE IV
ANOVA RESULTS FOR SEASONS

Season	P-value	Means are significantly different (number of pairs)
Spring	0.011	Yes (1)
Summer	1.491E-10	Yes (16)
Monsoon	3.475E-14	Yes (23)
Autumn	4.641E-4	Yes (3)
Winter	2.811E-6	Yes (9)

the second approach of SUHI indicators based on LU/LC and administrative borders. The pattern of deviation from mean is similar across the seasons, but the quantitative value differs. The SUHI intensity is the highest in autumn, followed by summer, spring, and winter. The statistical LST values, calculated regardless of LU/LC, show a range of 6.4° C, a mean magnitude of 3.5° C, and a standard deviation of 1.8° C. In the group of indicators based on LU/LC, five indicators have a positive value. The least values for indicators based on LU/LC are observed in the monsoon, as was the case in seasonal variation in the LCZs.

B. Statistical Analysis of SUHI Intensity Using ANOVA and Tukey Test

The LCZ classes are classified based on the understanding that the composition of urban form and function will create a distinct local thermal climate. ANOVA is used to identify the seasons with distinctive LCZ. It is initiated with a null hypothesis, i.e., there is no difference in the mean of the LCZ groups from the mean of the season.

The population means are significantly different for all five seasons, at a 95% confidence level (see Table IV). Once the seasons have been highlighted, the pairs of LCZ with a significant difference in mean need to be delineated. The Tukey test is used to compare the means. The test generated a varying number of season-wise pairs (see Table IV). Monsoon has 23 significant pairs, which is unexpected because the range of dispersion from the mean of the LST of LCZs is the least for the monsoon. The SUHI intensity in terms of LCZ difference is maximum for summer, 1.92–3.42° C, subsequently followed by winter from 2.75 to 3.66° C and monsoon from 1.28 to 2.34° C. There are six pairs of LCZ, which have a significant difference through all seasons (see Fig. 5).

C. Relationship Between "Urban" and "Urban Form" Using Pearson Correlation Analysis

In order to quantify the relationship between "urban" (using SUHI indicators) and the physical characteristics of the city "urban form" (using the differences in surface temperature between LCZs), a set of scatterplots is generated regardless of seasons (see Fig. 6). Each SUHI indicator is plotted against the possible corresponding difference of LCZ pairs (see Table V). The average of the four prominent urban forms, LCZ 3—compact low-rise, LCZ 5—open mid-rise, LCZ 6—open low-rise, and LCZ 8—large low-rise, is plotted along with individual urban built LCZs (3, 5, 6, and 8). The relationship can be understood in terms of the Pearson r correlation coefficient.

The strongest linear relationship (correlation coefficient 0.93) is observed between indicator "Urban∗-agriculture" and LCZ pairs 5 and D as well as the pairs 3 and D and 3568 and D (correlation coefficient 0.90)—[see Fig. 6(d)]. The "Urban∗-water" indicator has the highest correlation of 0.91 with LCZ pair 5 and G [see Fig. 6(a)]. The average of all urban forms (LCZ 3, 5, 6, and 8) has a strong linear relationship with indicators

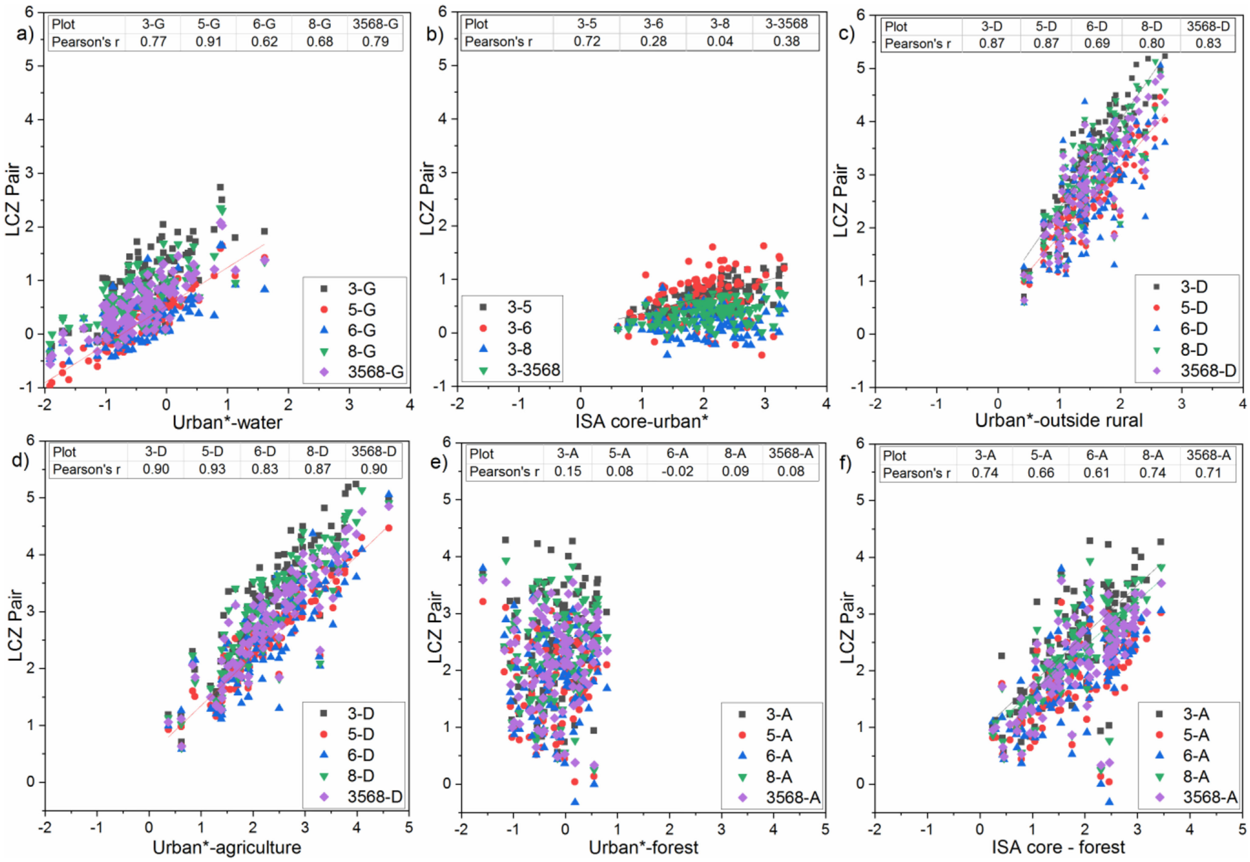

Fig. 6. Relationship between SUHI indicators and LCZ differences.

TABLE V
LCZ PAIRS CORRESPONDING TO SUHI INDICATORS

	Indicator	Corresponding LCZ pair
1	Urban*—outside rural	3-D, 5-D, 6-D, 8-D and 3,5,6,8-D
2	ISA core—urban*	3-5, 3-6, 3-8 and 3-3568
3	Urban*—water	3-G, 5-G, 6-G, 8-G and 3,5,6,8-G
4	Urban*—forest	3-A, 5-A, 6-A, 8-A and 3,5,6,8-A
5	ISA core—forest	3-A, 5-A, 6-A, 8-A and 3,5,6,8-A
6	Urban*—agriculture	3-D, 5-D, 6-D, 8-D and 3,5,6,8-D

"Urban∗-agriculture" at 0.90 and "Urban∗-outside rural" at 0.83 [see Fig. 6(c)]. However, in a scatterplot, the highest correlation coefficient is seen with either LCZ 3 (compact low-rise) or LCZ 5 (open mid-rise). Thus, "urban" cannot just be defined as an average of urban forms.

Fig. 6 is constructed using all available data regardless of seasons. However, it is essential to analyze the seasonal differences. Fig. 7 shows the correlation coefficients for "urban"-based SUHI indicators, and the differences in mean LST observed for LCZs, which are based on "urban form."

The strongest linear relationship is observed for the monsoon, followed by summer. The highest correlation value of 0.95 is observed for the "Urban∗-agriculture" indicator with LCZ difference of "5-D." The indicator "Urban∗-agriculture" has the strongest linear relationship with LCZs pairs across all seasons as compared to other indicators.

The transitional months of spring and autumn have consistently low correlation coefficients for all indicators and LCZ pairs. The correlation is high (0.72) when the LCZ difference is calculated between LCZ 3 (compact low-rise) and LCZ 5 (open mid-rise) when compared to LCZ 6 (open low-rise), LCZ 8 (large low-rise), and the average of several built-up LCZs (3, 5, 6, and 8). Winter generally shows a low correlation except for the indicator "Urban∗-water" with the LCZ difference of "5-G," for which it has a value of 0.93. LCZ 8 (large low-rise) and LCZ 3, 5, 6, and 8 have a correlation coefficient of 0.90 with one indicator, "ISA core-forest," during the monsoon.

IV. DISCUSSION

The work presented here is a study of the seasonal variation of SUHI for the Delhi city region to delineate heat-stressed zones. It utilizes two approaches for the purpose. The first is the conventional approach of SUHI indicators [21], [22], which distinguishes "urban" from "rural" using administrative borders. The second is the relatively recent LCZ approach [24], which contemplates "urban form" to understand the local climatic variations in the thermal environment. The present work also addresses the relationship between the LST of areas used for SUHI

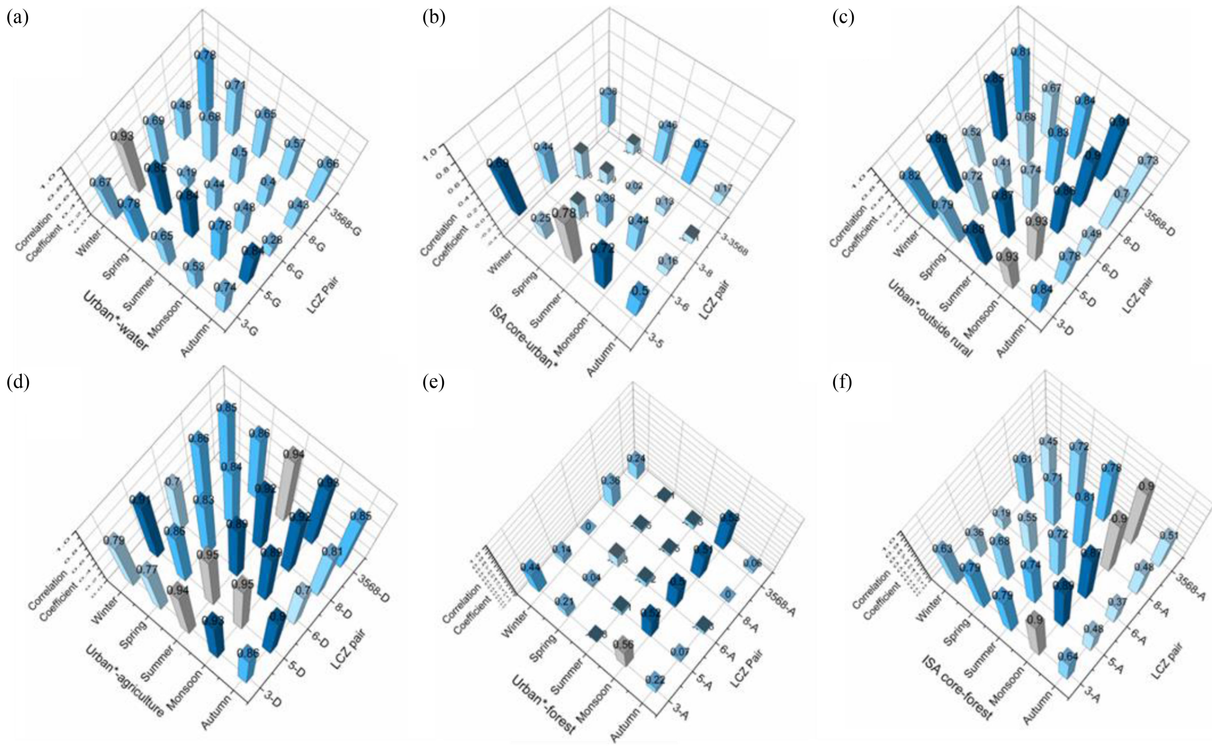

Fig. 7. Seasonal analysis of the relationship between "urban" indicators and "urban form" LCZs.

indicators delineation, the so-called "urban," and the physical characteristics of the city, the "urban form"—referred as LCZs. This study is among the first to utilize LCZs for SUHI analysis in Delhi for multiple seasons on a regional scale, enabling comparisons of SUHI intensity with other cities in the world.

SUHI intensity is conventionally estimated using the temperature difference between "urban" and "rural." In all of the previous studies focused on Delhi, the classification of "urban" is ambiguous. Some researchers use "built-up" areas [19], [17], others divide dense built-up areas into two classes [14], refer to canopy density [18], or land use—divided into residential, commercial, and industrial [15], [16]. This is one of the two approaches used in presented study, and serves to define conventional SUHI indicators (see Table III). The second approach uses an LCZ classification approach to define urban forms, and, then, the SUHI intensity is estimated as the surface temperature difference between LCZs.

Previous studies report night-time SUHI intensity for Delhi as 4° C in October, as the difference between "high, dense built up" and "vegetation" [14], 4–6° C in March and 0–2° C during the monsoon, as the difference between "built up" and "rural," and 3° C in October as the difference between "urban" and "vegetation" [15]. The results of the current study show an SUHI intensity of 3.5° C, as the difference between LCZ 3 (compact low-rise) and LCZ D (low plants), which occurs in summer, followed by spring, autumn, and winter. In a conventional approach, "rural" is either labeled "green areas" [18], or is not defined [19], [17]. Mohan *et al.* [18] identified the problem of "rural" reference in a megacity such as Delhi, which has so many outgrowths that no unadulterated "rural" reference is available. The conventional approach lacks repeatability of the experiments, since its definition of urban and rural form is unclear. The LCZ approach presented in the current work uses LCZ D (low plants) as the rural reference corresponding to the agricultural area surrounding Delhi. LCZ studies conducted for Uppsala, Nagano, and Vancouver [26] also found LCZ D (low plants) to be the appropriate rural reference.

The SUHI intensity based on the LCZ method observed in the present study is comparable to previously published papers. Most of the LCZ studies for other cities [24], [26], [27] also report compact urban LCZ classes (1—compact high-rise, 2—compact mid-rise, and 3—compact low-rise) as the ones with maximum nocturnal UHI intensity with reference to LCZ D (low plants). The compact LCZ classes (1–3) have low sky view factor, which limits radiative cooling, and low height to width (H/W) ratio, which blocks the flow of air. The results of the present study are also comparable to the results obtained for Prague and Brno [28], which show that compact low-rise (LCZ 3) is among the warmest LCZs.

The statistical significance of SUHI intensity results for the current research is tested using ANOVA. The analysis shows that all seasons have a statistically significant difference of LST mean. This gives support to the contention that various LCZs exist in a megacity, and that these zones deviate substantially from the regional climate. This conclusion is further strengthened by the results of the Tukey test, used to determine pairs of LCZs with a significantly different thermal behavior. The maximum numbers of thermally distinct LCZs occur during the monsoon, followed by summer and winter. This result is worth emphasizing, particularly because 33% of the SUHI studies focus only on summer, and just 23% of the existing studies analyze SUHI through all the seasons [42]. The high number of distinct thermal zones during the monsoon can be attributed to the high elevation angle of the sun and urban runoff on impervious surfaces. The transition months of autumn and spring have only one pair of distinct LCZs, which still requires further inquiry because the thermal range is comparable to summer (see Fig. 5). Two urban forms, compact low-rise (LCZ 3) and large low-rise (LCZ 8), have been identified as the heat-intensive LCZs. They account for 14% of the total area for Delhi.

The correlation between SUHI calculated using conventional indicators and LST differences across LCZs, i.e., the "urban" and "urban forms," is the strongest during the monsoon, followed by summer. These two seasons include the months with the maximum sun elevation angle, and so the maximum LST values. The indicator "Urban-agriculture" has the highest Pearson correlation coefficient, 0.93, with the LCZ difference of open mid-rise (LCZ 5) and low plants (LCZ D) [see Fig. 7(d)]. The highest correlation of all SUHI indicators other than "urban-agriculture" is observed with compact low-rise (LCZ 3) and open mid-rise (LCZ 5), rather than with open low-rise (LCZ 6), large low-rise (LCZ 8), or average of urban forms (3-5-6-8) (see Figs. 6 and 7). The results presented here show that using "urban form" based on an LCZ scheme works much better than using SUHI indicators based on a generalized "urban" classification because the "urban form" indicators allow determination of the specific physical characteristics causing significant thermal contrasts.

The study presented here has also some limitations. More city regions of the world need to be studied to allow generalization of the results; particularly city-regions where the "urban" and "rural" areas are hard to distinguish. Some such city regions are Mumbai, Cape Town, Mexico City, and São Paulo, among others. Therefore, the authors speculate that when a different city with different surroundings is considered, the relationship between SUHI indicators and LCZ difference might vary. Furthermore, given the fact that SUHI analysis is dependent on the spatial resolution of available thermal images and the satellite overpass time, a different satellite sensor like ASTER or Landsat may produce diverse results. However, as the physical mechanism behind the formulation of SUHI in each city is the same, we expect that eventual differences would be minor.

V. Conclusion

The SUHI intensity obtained from conventional SUHI indicators and LCZs are comparable, but the LCZ approach provides a finer-grained understanding of the relationship between urban form and SUHI. The night-time maximum SUHI intensity using the conventional, generalized "urban"-based indicator approach is 3.3° C, observed for "Inside urban–inside rural" in autumn, followed by summer, spring, and winter, and at 2.3° C, is the least during the monsoon. The maximum SUHI intensity using the LCZ approach for Delhi is 3.5° C, between LCZ 3 (compact low-rise) and LCZ D (low plants), occurring in summer, followed by spring, autumn, winter, and decreasing to the lowest value of 2.5° C in the monsoon. The SUHI indicator "Urban-agriculture" has the strongest linear relationship (correlation coefficient of 0.93) with the LST difference between LCZ 5 (open mid-rise) and LCZ D (low plants). The results indicate that eventual SUHI mitigation strategies should be focused on the heat-stressed LCZ 3 (compact low-rise) and LCZ 8 (large low-rise) zones.

This study advocates the LCZ approach over the conventional SUHI indicators, as "urban" and "rural" areas cannot be clearly delineated for rapidly expanding urban conurbations such as the Delhi city region. The LCZ approach helps us understand the dependency of SUHI intensity on the type of urban form, which is much more useful for focused mitigation than vague, overly broad classifications of "urban" and "rural." The results presented here also show the importance of seasonal analysis of SUHI intensity rather than only summer daytime analysis. In order to generalize the findings of the study, studies of other large city regions, utilizing different satellite sensors, and daytime images is required.

Acknowledgment

The authors would like to thank Dr. Richa Sharma, Research scientist at the Centre for Environmental Health; Public Health Foundation of India (Delhi) for sharing the WUDAPT-based LCZs of Delhi with us.

References

[1] C. S. B. Grimmond, "Progress in measuring and observing the urban atmosphere," *Theor. Appl. Climatol.*, vol. 84, nos. 1–3, pp. 3–22, Feb. 2006.

[2] A. J. Arnfield, "Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island," *Int. J. Climatol.*, vol. 23, no. 1, pp. 1–26, 2003.

[3] T. R. Oke, "The energetic basis of the urban heat island," *Q. J. R. Meteorol. Soc.*, vol. 108, no. 455, pp. 1–24, 1982.

[4] J. A. Voogt and T. R. Oke, "Thermal remote sensing of urban climates," *Remote Sens. Environ.*, vol. 86, no. 3, pp. 370–384, 2003.

[5] F. Becker and Z.-L. Li, "Surface temperature and emissivity at various scales: Definition, measurement and related problems," *Remote Sens. Rev.*, vol. 12, nos. 3–4, pp. 225–253, Jan. 1995.

[6] T. N. Carlson, J. K. Dodd, S. G. Benjamin, and J. N. Cooper, "Satellite estimation of the surface energy balance, moisture availability and thermal inertia," *J. Appl. Meteor.*, vol. 20, no. 1, pp. 67–87, Jan. 1981.

[7] J. A. Azevedo, L. Chapman, and C. L. Muller, "Quantifying the daytime and night-time urban heat island in Birmingham, UK: A comparison of satellite derived land surface temperature and high resolution air temperature observations," *Remote Sens.*, vol. 8, no. 2, Feb. 2016, Art. no. 153.

[8] M. Lazzarini, P. R. Marpu, and H. Ghedira, "Temperature-land cover interactions: The inversion of urban heat island phenomenon in desert city areas," *Remote Sens. Environ.*, vol. 130, pp. 136–152, Mar. 2013.

[9] A. Buyantuyev and J. Wu, "Urban heat islands and landscape heterogeneity: Linking spatiotemporal variations in surface temperatures to land-cover and socioeconomic patterns," *Landscape Ecol.*, vol. 25, no. 1, pp. 17–33, Sep. 2009.

[10] D. R. Streutker, "Satellite-measured growth of the urban heat island of Houston, Texas," *Remote Sens. Environ.*, vol. 85, no. 3, pp. 282–289, 2003.

[11] J. A. Sobrino, R. Oltra-Carrió, G. Sòria, R. Bianchi, and M. Paganini, "Impact of spatial resolution and satellite overpass time on evaluation of the surface urban heat island effects," *Remote Sens. Environ.*, vol. 117, pp. 50–56, 2012.

[12] P. Zhang, M. L. Imhoff, L. Bounoua, and R. E. Wolfe, "Exploring the influence of impervious surface density and shape on urban heat islands in the northeast United States using MODIS and Landsat," *Can. J. Remote Sens.*, vol. 38, no. 4, pp. 441–451, 2012.

[13] I. D. Stewart, "A systematic review and scientific critique of methodology in modern urban heat island literature," *Int. J. Climatol.*, vol. 31, no. 2, pp. 200–217, 2011.

[14] J. Mallick, A. Rahman, and C. K. Singh, "Modeling urban heat islands in heterogeneous land surface and its correlation with impervious surface area by using night-time ASTER satellite data in highly urbanizing city, Delhi-India," *Adv. Space Res.*, vol. 52, no. 4, pp. 639–655, 2013.

[15] Y. Kant, B. D. Bharath, J. Mallick, C. Atzberger, and N. Kerle, "Satellite-based analysis of the role of land use/land cover and vegetation density on surface temperature regime of Delhi, India," *J. Indian Soc. Remote Sens.*, vol. 37, pp. 201–214, 2009.

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

[17] R. B. Singh, A. Grover, and J. Zhan, "Inter-seasonal variations of surface temperature in the urbanized environment of Delhi using Landsat thermal data," *Energies*, vol. 7, no. 3, pp. 1811–1828, 2014.

[18] M. Mohan, Y. Kikegawa, B. R. Gurjar, S. Bhati, A. Kandya, and K. Ogawa, "Urban heat island assessment for a tropical urban airshed in India," *Atmospheric Climate Sci.*, vol. 2, no. 2, 2012, Art. no. 127.

[19] A. K. Pandey *et al.*, "Spatio – temporal variations of urban heat island over Delhi," *Urban Climate*, vol. 10, no. Part 1, pp. 119–133, 2014.

[20] K. Liu, H. Su, X. Li, W. Wang, L. Yang, and H. Liang, "Quantifying spatial temporal pattern of urban heat island in Beijing: An improved assessment using land surface temperature (LST) time series observations from LANDSAT, MODIS, and Chinese new satellite GaoFen-1," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 9, no. 5, pp. 2028–2042, May 2016.

[21] N. Schwarz, S. Lautenbach, and R. Seppelt, "Exploring indicators for quantifying surface urban heat islands of European cities with MODIS land surface temperatures," *Remote Sens. Environ.*, vol. 115, no. 12, pp. 3175–3186, 2011.

[22] N. Schwarz, U. Schlink, U. Franck, and K. Großmann, "Relationship of land surface and air temperatures and its implications for quantifying urban heat island indicators—An application for the city of Leipzig (Germany)," *Ecol. Indicators*, vol. 18, pp. 693–704, 2012.

[23] L. Gawuc and J. Struzewska, "Impact of MODIS quality control on temporally aggregated urban surface temperature and long-term surface urban heat island intensity," *Remote Sens.*, vol. 8, no. 5, May 2016, Art. no. 374.

[24] I. D. Stewart and T. R. Oke, "Local climate zones for urban temperature studies," *Bull. Am. Meteor. Soc.*, vol. 93, no. 12, pp. 1879–1900, 2012.

[25] B. Bechtel *et al.*, "Mapping local climate zones for a worldwide database of the form and function of cities," *ISPRS Int. J. Geo-Inf.*, vol. 4, no. 1, pp. 199–219, Feb. 2015.

[26] I. D. Stewart, T. R. Oke, and E. S. Krayenhoff, "Evaluation of the 'local climate zone' scheme using temperature observations and model simulations," *Int. J. Climatol.*, vol. 34, no. 4, pp. 1062–1080, Mar. 2014.

[27] A. K. Nassar, G. A. Blackburn, and J. D. Whyatt, "Dynamics and controls of urban heat sink and island phenomena in a desert city: Development of a local climate zone scheme using remotely-sensed inputs," *Int. J. Appl. Earth Observ. Geoinformation*, vol. 51, no. Supplement C, pp. 76–90, Sep. 2016.

[28] J. Geletič, M. Lehnert, and P. Dobrovolný, "Land surface temperature differences within local climate zones, based on two central European cities," *Remote Sens.*, vol. 8, no. 10, Sep. 2016, Art. no. 788.

[29] M. Cai, C. Ren, Y. Xu, K. K.-L. Lau, and R. Wang, "Investigating the relationship between local climate zone and land surface temperature using an improved WUDAPT methodology – A case study of Yangtze River Delta, China," *Urban Climate*, vol. 24, pp. 485–502, Jun. 2017.

[30] L. Zhongli and X. Hanqiu, "A study of urban heat island intensity based on "Local Climate Zones": A case study in Fuzhou, China," in *Proc. 4th Int. Workshop Earth Observ. Remote Sens. Appl.*, Jul. 2016, pp. 250–254.

[31] U. N. Desa, "World urbanization prospects, the 2018 revision," Population Division, Department of Economic and Social Affairs, United Nations Secretariat, New York, NY, USA, 2018. [Online]. Availaible: https://www.un.org/development/desa/publications/2018-revision-of-world-urbanization-prospects.html

[32] B. R. Gurjar *et al.*, "Human health risks in megacities due to air pollution," *Atmospheric Environ.*, vol. 44, no. 36, pp. 4606–4613, 2010.

[33] A. P. Sati and M. Mohan, "The impact of urbanization during half a century on surface meteorology based on WRF model simulations over National Capital Region, India," *Theor. Appl. Climatol.*, vol. 134, pp. 309–323, 2017.

[34] C. Chandramouli and R. General, "Census of India 2011," in *Provisional Population Totals*. New Delhi, India: Government of India, 2011.

[35] B. Bechtel and C. Daneke, "Classification of local climate zones based on multiple earth observation data," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 5, no. 4, pp. 1191–1202, Aug. 2012.

[36] L. See *et al.*, "Developing a community-based worldwide urban morphology and materials database (WUDAPT) using remote sensing and crowdsourcing for improved urban climate modelling," in *Proc. Joint Urban Remote Sens. Event*, 2015, pp. 1–4.

[37] J. A. Azevedo, L. Chapman, and C. L. Muller, "Quantifying the daytime and night-time urban heat island in Birmingham, UK: A comparison of satellite derived land surface temperature and high resolution air temperature observations," *Remote Sens.*, vol. 8, no. 153, 2016.

[38] J. Zhang and Y. Wang, "Study of the relationships between the spatial extent of surface urban heat islands and urban characteristic factors based on Landsat ETM+ Data," *Sensors*, vol. 8, pp. 7453–7468, 2008.

[39] R. Pongrácz, J. Bartholy, and Z. Dezső, "Application of remotely sensed thermal information to urban climatology of central european cities," *Phys. Chemistry Earth, Parts A/B/C, Bio-, Agro, Urban Climatology*, vol. 35, pp. 95–99, 2010.

[40] J. Ching *et al.*, "World urban database and access portal tools (WUDAPT), an urban weather, climate and environmental modeling infrastructure for the Anthropocene," *Bull. Am. Meteorological Soc.*, vol. 99, no. 9, pp. 1907–1924, 2018.

[41] B. Bechtel *et al.*, "Generating WUDAPT level 0 data – current status of production and evaluation," *Urban Climate*, vol. 27, pp. 24–45, 2019.

[42] D. Zhou *et al.*, "Satellite remote sensing of surface urban heat islands: Progress, challenges, and perspectives," *Remote Sens.*, vol. 11, no. 1, 2019, Art. no. 48.

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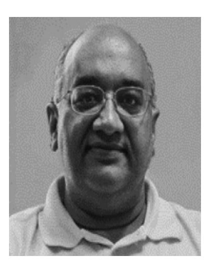

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