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# 'Fit for Purpose' Urban Heat Island Effect Study Methodology for Indian Cities

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## Highlights

- A systematic review of the Urban Heat Island Effect (UHIE) assessment literature and practices.
- Derivations and defining the Level of Detail (LoD) classification.
- Identifying the purposes of the UHIE study and categorizing the LoD for a ‘Fit for Purpose’.
- Developing a commonly agreed methodology for Indian Cities.

## Abstract

The paper recognizes that the Urban Heat Island Effect (UHIE) occurs primarily due to urbanization impacting land surface characteristics, where the blue-green cover is replaced with complex-built fabric and increased anthropogenic heat emissions within urban areas. Without a common agreed-upon methodology with specific objectives that cities wish to accomplish, Indian cities are adopting varied methods to assess UHIE that do not help them attain the predefined objectives and are often found to be less scientific. This paper proposes a standardized methodology and underpins its argument on two frameworks, ‘Fit for the Purpose’ and ‘Level of Details,’ making it easier to adopt. Such efforts are expected to help cities account for the UHIE assessment with specific objectives that cities can optimize with available data and human and economic resources. The paper relies on a systematic literature review and considers the ground realities to develop the methodology. The proposed framework could be one of a kind to be adopted in India, helping cities evaluate their context and navigate them to solutions. It also aims to balance the suitable trade-off between data fidelity and decision-making efficiency, tailored to specific needs and constraints.

**Keywords:** urban heat island effect, level of details, fit for purpose, heat action plan, outdoor thermal comfort.

## Introduction

The paper is structured into four sections: Introduction, Methodology, Discussions, and Recommendation. The introduction provides an overview of UHIE, its consequences, and the existing research gaps. It also introduces two terminologies: ‘Fit for the Purpose’ (FFP) and ‘Level of Detail’ (LoD). The methodology section relies on the systematic literature review to develop a scientific rationale by identifying the critical objectives, methods for mapping and assessing UHI variability, critical study parameters, and their datasets. The methodology also highlights the critical reasoning for how this standardized methodology is expected to aid the gaps before illustrating the proposed FFP framework for UHIE assessment with its LoD characterization. The discussion section elaborates on the methodology for one sample purpose, with key datasets and their associated LoDs required to meet the objectives and to conclude the proposed framework. It also summarizes the methodology for mapping and assessment for each purpose and their best possible LoDs against their objectives. The recommendation section highlights the level of resources necessary for each purpose and their LoDs.

With emerging urbanization, UHIE became one of the most frequently examined themes by urban experts since it accelerates environmental hazards and human mortality. The ongoing research on the UHIE has integrated urban planning, sprawl, and climate change phenomena, three of the most significant environmental concerns of the 20th century. UHIE is also crucial in energy consumption as it is associated with the urban microclimate, neighbourhood morphology, etc. Between 1990 and 2012, greenhouse gas emissions in India and Pakistan nearly doubled, and the urban areas accounted for more than 60% of that [1]. The countries with lower-middle and lower-income groups will be most adversely affected and reportedly lose 4% and 1.5% of their GDP by 2030, which is also projected to increase by up to 9% by the end of 2100 [2]. Therefore, state governments, municipalities, and urban planning authorities must develop the appropriate policies, pilot programs, necessary toolkits, and capacity-building to reduce heat stress, greenhouse gas emissions, energy conservation, and to improve thermal comfort conditions [3].

A recently published study from the Indian Meteorological Department (IMD) mentioned that heatwaves have significantly increased by about 24% during 2010-19 compared to 2000-2009, while they also highlighted a spike in mortality rates of 27 % during that period [4]. A recent study mapped the UHI intensity across the major Indian cities, and the results ranged between 1.76 to 4.6 °C [5]. Authorities in India are stepping up their efforts, drawing inspiration from Ahmedabad's landmark Heat Action Plan (HAP) [6]. Indian Meteorological Department (IMD) and National Disaster Management Authority (NDMA) have already designated 23 states (such as Delhi, Rajasthan, Maharashtra, etc.) to implement the HAP as a comprehensive extreme heat alert system and preparedness strategy [7]. In 2019, NDMA laid the guidelines [8] as a roadmap for the Indian states and cities to develop the context-specific HAP integrating urban planning, meteorology, and public health infrastructure. Besides heat hazard analysis, IMD also works on three-tier impact-based forecasts and risk-based warning systems [9]. As per the recent publication [10], they are planning to roll out a heat index by mapping the critical meteorological parameters (relative humidity, max., and min. air temperature, duration of heat spell, wind) to provide a real feel of temperature along with a color-based warning system [11]. With the recent urbanization trend, mapping of UHI hotspots by focusing on hyperspectral aerial imagery from remote sensing [12], increasing networks of metadata collection stations with low-cost sensors, and assessing the dual threats (considering heat waves) on microclimate and thermal discomfort is imperative for effective policy making and preparation of climate resilient action plan [3]. The National Institute of Urban Affairs (NIUA) is working on an assessment framework focusing on UHIE, urban planning, energy use, and blue-green networks for climate-smart cities and holistic revision in the existing planning guidelines [13].

From the existing UHI studies, critical issues such as (i) inconsistent data mapping due to the unavailability of datasets, (ii) absence of ground truthing to validate the satellite imageries, (iii) optimum spatio-temporal resolution, and (iv) determining the spatial grid for station point distribution, identified during the data collection and mapping [14]. Moreover, the concurrent gaps with numerical modelling and canopy level simulation studies can be concluded as (i) idealized parameter settings used for the model-boundary conditions; (ii) the actual context and target parameters do not get reflected due to the simplification of 3D land use land cover modelling techniques; (iii) the unsatisfactory accuracy of the numerical simulations [15]. Determining and assessing the urban energy budget and its effects on UHI intensity is crucial in the UHIE study. A recent study [16] has also indicated the need for standardized metrics to determine a city's energy budget model. Presently, to manage the heat waves, UHI, and developing an integrated policy to mitigate the UHIE and thermal discomfort, (i) cities cannot evaluate the required datasets, appropriate boundary conditions, and optimized assessment metrics, (ii) multiple approaches without scientific evidence lead to an outcome that may not be appropriate to the context, (iii) the absence of a commonly agreed methodology does not help in coordination at the national level to access the risk and mitigation measures on the similar platform eliminating the possibility of cross-learning at the same time. The proposed LoD-based FFP framework will allow decision-makers to develop common strategies and help share their success and failure stories.

### Level of details (LoDs)

The Level of Detail (LoD) refers to a technique that involves representing objects or data at different levels of complexity or detail, depending on the specific requirements or constraints of the application.

Such concepts are used in several fields, including computer graphics, data visualization, and medical sciences. The LoD concept allows for the efficient representation of larger datasets. Considering every available single data point can be overwhelming to process. Therefore, lower levels of detail can be used to present an overview of the data. The higher LoD can be progressively revealed as decision-makers zoom in or interact with the dataset, providing more specific information or granular views.

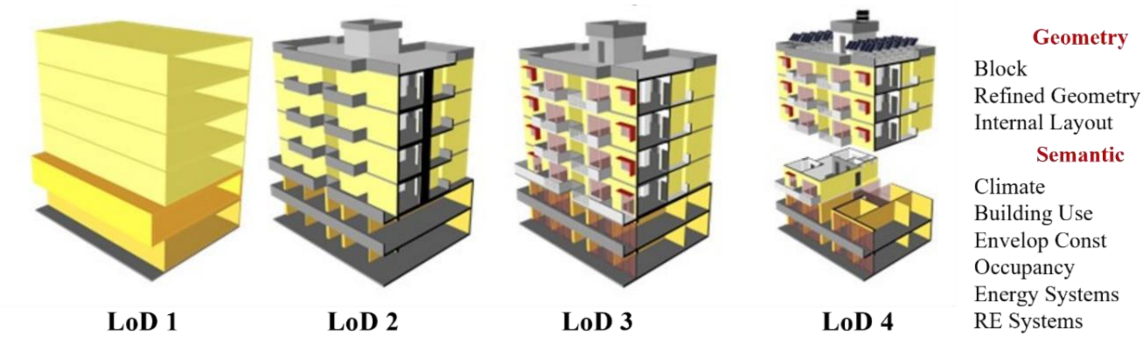

*Figure 1: An example of LoD characterization adopted for Urban Building Energy Modelling (UBEM)* [17]

As illustrated in Figure 1, suitable LoD characterization has been developed for an FFP framework for urban building energy modelling (UBEM) to aid in the persistent gaps (e.g., accuracy, classification, and complexity of modelling inputs, standardized metrics, reliability of calibration methods) in modelling, simulation and enable highly targeted data collection approach. In the context of the UHIE mapping and assessment, if the objective is to determine the hotspots across the city, one needs only a snapshot or single point in time data at peak hours with values of only four or five data points. But suppose the objective is to assess urban microclimate and to determine the outdoor thermal comfort by integrating the universal thermal climate index (UTCI). One will need consistent data over a few days at an hourly interval and for about 15 to 16 data sets across multiple stations. The LoD approach aims to strike a suitable trade-off between data fidelity and decision-making efficiency tailored to the specific needs and constraints of the system or application.

### Fit for purpose

The underlying principle of developing the standardized UHIE methodology is to recognize the objective of the exercise at the very first instance. Any activity that needs to be carried out to understand the impact of UHIE needs to identify the target on which UHIE may have an effect. This paper has adopted 'Fit-For-Purpose' (FFP) as a terminology based on earlier work by the same authors to identify the objective of the exercise. The methodology to understand the impact of the UHIE will depend upon FFP.

The FFP refers to a framework that helps define the suitable or appropriate aim that needs to be achieved. It also helps customize the methodology to attain the specific solution. The FFP often involves accessing and ensuring that the methodology's qualities, features, functionality, performance, and reliability lead the process to the expected outcomes. The LoD characterization for the required datasets is evaluated in this paper against four critical purposes for comprehensive UHIE mapping and assessment to develop the FFP framework. The purposes are primarily concluded as an integrated measure for multiple interlinked objectives from the key findings of the literature.

### Aims and objectives of the study

The study aimed to develop a LoD-based FFP framework for Indian cities as a standardized method for mapping and assessment of UHIE without compromising the accuracy of the results. This proposed framework will aim to address all the critical objectives regarding UHIE assessment and the required data sets with their suitable LoDs, which will be context-specific and adaptable based on the complexity of the study objective (e.g., spatio-temporal resolution, accuracy), projected outcome and available resources (e.g., manpower/expertise, cost, instrumentation, and time).

## Methodology

### Literature review

The paper adopted a systematic review of the extensive work carried out internationally and nationally for a comprehensive literature review. The existing studies regarding urban climate, built morphology, and their impact on UHIE were reviewed to comprehend the dynamics and mechanism of an urban environment with the changing urban characteristics before mapping the spatio-temporal variability of UHI. At the same time, the urban spatial scales and datasets have been evaluated for mapping and assessment of canopy layer urban heat island (CLUHI) and surface layer urban heat island (SUHI), with their critical technical parameters. Studies adopted rigorous measurement protocols and field surveys to validate the empirical/numerical models developed for a specific urban region. Ground truthing was also integrated into the studies to enhance the accuracy of the hyperspectral satellite data boundary conditions of simulation models and improve the overall reliability of the study outcome. The existing research gap and limitations were also reviewed to strengthen the evidence-based rationale for the study. The overall structure adopted for the literature review is illustrated in Figure 2.

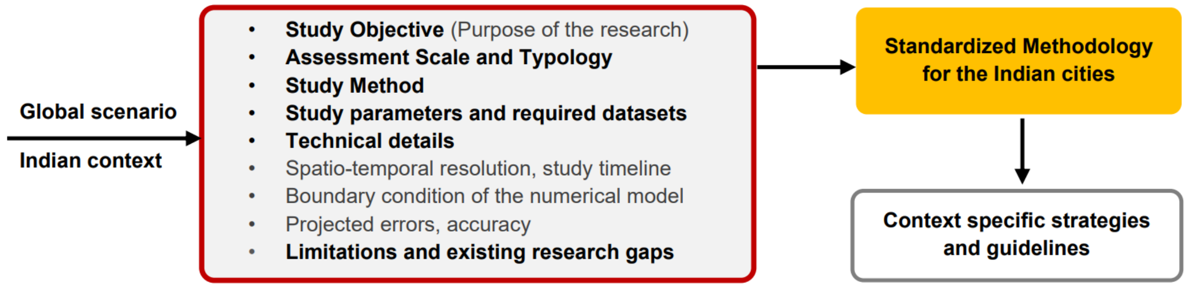

*Figure 2: Structure of literature review adopted for the study*

**The outcome of the literature review**

It is crucial to determine the key purposes/objectives adopted in the empirical studies for developing an appropriate rationale before concluding them in the proposed standardized framework. The key findings are summarized in Table 1. The studies mostly adhered to determine the hotspots and assess the projected impact of LULC/urban sprawl, surface characteristics, urban geometry on land surface temperature (LST), and urban microclimate.

Surface layer UHI (SUHI) studies mostly concentrated on investigating the spatiotemporal variability of LST and assessing their co-relationship with the changing LULC pattern. They have been associated with the land surface layer and conducted mostly at the meso scale. However, The Canopy layer UHI (CLUHI) studies are mostly conducted at the local or micro-scale and conclude the urban canopy layer (UCL) or building canopy layer (BCL), as illustrated in Table 2.

*Table 1: Major study purposes/objectives concluded from the literature*

| Study objective/purposes | References |
|---|---|
| Mapping and assessment of hotspots, UHI intensity | [18], [19], [20-27], [28-30] |
| Assessing the impact of land use land cover (LULC) changes/ urban sprawl/ urbanization | [20], [23], [31-36] |
| Determining the impact of surface characteristics on UHI intensity | [37-40] |
| Assessing the built environment on microclimate/ improving the outdoor thermal comfort | [41-50] |
| Reducing building energy consumption/ cooling load/ GHG emission | [51-54] |

*Table 2: The scale of UHI assessments concluded from the literature*

| UHI Type | Horizontal scale | | Vertical scale | | References |
|---|---|---|---|---|---|
| SUHI | Meso scale (city/regional level) ~ upto10's km | | Land surface layer | | [20-23], [55] |
| CLUHI | Local-scale (neighbourhood level) ~ 1 to <10 km | Micro-scale (street/block level) ~ 1 to 100's m | Urban canopy layer (UCL) | Building canopy layer (BCL) | [18], [37], [56-59] |

Studies on UHI variations have concentrated on either temporal [21], [23], [60], [61] or spatial anomalies [62], [63] and, in some studies, both [60], [64], [65]. The ratio between the SUHI-based studies considering land surface temperature (LST) acquired by remote sensing technique [22], [23], [26-29] with Landsat, MODIS, etc., and others that examined the intensity of CLUHI using meteorological data (air temperature, relative humidity, and solar radiation) acquired from either fixed weather stations [66], [67] or mobile traverse [18], [68], [69] was high among those that were reviewed. Moreover, some of the CLUHI-based studies integrated automatic weather stations [32], [70], WRF modelling [71-72], artificial neural network-based algorithms, and field campaigns for a comprehensive study outcome.

For the CLUHI-based assessment, the Weather Research and Forecasting (WRF) model coupled with Urban/Regional Climate Model (UCM/RCM) as meso-scale [16], [73] and experimental CFD simulation using the appropriate turbulent model [18], [74] [75] as microscale modelling was identified as the commonly adopted tools to assess the UHIE magnitude and critical hotspots. Urban microclimate simulation with ENVI Met and ANSYS Fluent aided with various turbulence models have been conducted at the block level [76-78], focusing on the HVAC field and indoor thermal comfort and at the neighbourhood level [79-83] investigating the influence of vegetation, water bodies, building morphology, ventilation corridors, and anthropogenic heat on the urban thermal environment considering the thermal comfort indices, e.g., Universal Thermal Climate Index (UTCI), Physiological Equivalent Temperature (PET), Predicted Mean Vote (PMV), etc.

Moreover, multivariate statistical models were applied to determine the impact of urban sprawl, urban morphology, and meteorological indices on UHI intensity with their spatiotemporal variation. They also validated the simulation results and hypothetical assumptions with the real-time scenario. For CLUHI assessment, Multiple linear regression (MLR)-based models were extensively used. They frequently obtained high degrees of accuracy, as evidenced by the previous studies [84-86], and sometimes coupled with random forest (RF) models [87]. However, in SUHI-based studies, limited research has been performed to establish simplified numerical tools to investigate the spatiotemporal changes of LST from satellite imagery datasets for a more extended period [31], [88], [89]. Multiple studies that acquired the primary data from Remote Sensing, GIS or LiDAR, have adopted statistical analysis such as- canonical correlation analysis (a multivariate analysis) [23], spatial autocorrelation, lag model (SLM) and the spatial error model (SEM) [90], Fractal analysis [91], Spearman correlation analysis, Automatic linear modelling algorithm [21], Ordinary least squares (OLS), Support vector machine (SVM), Random forest [92], Ordinary least squares (OLS) regressions [26], Spearman correlation analysis [93] to validate, error fix and assess the acquired thermal image by further processing to investigate the SUHI.

*Table 3: Study parameters and required datasets for UHIE study- as concluded from the literature study*

| Parameter | Data sets | Reference |
|---|---|---|
| Meteorology | Air temperature, Relative humidity, wind dynamics- speed and direction, solar radiation, cloud cover, Surface temperature | [36], [39], [55], [94-97] |
| Urban Infrastructure | Land use land cover classification. | [20], [23], [31], [32] |
| | Neighbourhood configuration (layout, setbacks, street geometry) | [46-50] |
| | Building geometry (form and height/no of floors) | [21], [23], [90], [92], [93], [98] |
| | Tree vegetation properties | [33-35] |
| Semantic data | Surface characteristics (albedo, emissivity, etc.) | [37-40] |
| | Building information (age, class of the property) | [45], [50] |
| Energy consumption | Cooling energy load | [51-54] |
| Thermal comfort | MRT, PET, UTCI, PMV, PPD | [41-45] |

### Benefits of determining LoDs and FFPs

The critical evaluation of the literature was carried out to overcome the gaps with probable integrated measures such as (i) developing a standardized research framework/methodology for UHIE, (ii) focusing on accurate boundary conditions for numerical modelling and specific metrics that allow the urban morphology and meteorological datasets to reflect their respective characteristics in the UHI assessment, and (iii) establish a composite scale based on the first two recommendation that can effectively quantify the degree of the UHI variability.

The LoD-based FFP framework will help to standardize the UHI assessment studies, enabling the city planners and managers to employ appropriate assessment techniques and metrics for data collection and analysis and to forecast future scenarios specific to the context. The method will also help to investigate the critical hotspots and other contributing factors to UHIE. The outcome will also aid decision-makers in developing coordinated strategies for comprehensive master planning and the policy-level guidelines in the public-private domain substantiated by setting future goals.

### Development of a fit-for-purpose methodology with LoD characterization

This document has concluded four purposes from the literature review (refer to Table 1). These four purposes can be further synthesized with their usefulness, probable outcome or targets (as illustrated in Table 4), methodology to conduct the assessment (e.g., data collection, mapping, analysis, and validation), required data sets with their LoD characterization, and a plan of action for a successful implementation, as a way forward from this proposed methodology.

*Table 4: Key purposes of the FFP framework of the UHIE study and their projected outcomes*

| Purposes | | Probable outcomes/targets |
|---|---|---|
| P1 | Development of a Heat Action Plan (HAP) | Mapping the present and future hotspots |
| | | Development of a composite heat vulnerability index |
| | | Developing a UHI mitigation performance index with a real-time monitoring system |
| P2 | Assessing the spatiotemporal dynamics of urban planning on UHI intensity | Reduction in anthropogenic heat from the building and transportation sector |
| | | Revision of policies (spatial planning, transportation, energy), building By-laws, energy codes |
| | | Integrated measures for local area plan / Transit orient development to limit urban sprawl and emphasize the nature-based solution (NBS) |
| P3 | Improving outdoor thermal comfort | Improving present and future microclimate scenarios and enhancing indoor thermal comfort at the building or unit level |
| | | Minimizing the cooling energy demand |
| | | Developing a support-based decision-making tool for low-carbon and climate adaptation |
| P4 | Reduction in the GHG emission | Developing and testing Urban energy modelling tools and alternate methodologies |
| | | Developing energy-space syntax and identifying trends in energy consumption |
| | | Energy forecasting of the present and future scenario |

Based on the increasing complexity, each study parameter with its datasets is assigned a suitable LoD from one to four, with one being the simplest and four being the most complex. The required datasets are categorized into seven critical parameters for assessing the four purposes related to the UHIE study, as illustrated in Table 5. They are adaptable, considering the resources and limitations of each study.

*Table 5: Proposed LoD characterization for a fit-for-purpose UHIE assessment framework*

| **Level of Detail** | **Study Parameters** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Meteorology** | **Urban Infrastructure** | **Semantic** | **Operational profile** | **Energy consumption** | **Spatial resolution** | **Temporal resolution** |
| LoD 1 | Air Temp. | LULC | Surface Characteristics | Deterministic-Single | Connected Loads | 1000 m. | Decadal |
| LoD 2 | LoD 1 + Surface Temp. | LoD 1+ Plot boundaries | LoD 1 + Building use | LoD 1 + Deterministic-Multiple | LoD 1 + Load profiles | 100 m | Annual |
| LoD 3 | LoD 2 + Relative Humidity + Solar Radiation | LoD 2+ Building footprint | LoD 2 + Age of property | LoD 2 + StochasticSpace based | LoD 2 + Metered data | 30 m | Monthly |
| LoD 4 | LoD 3 + Cloud cover + Wet bulb globe temp. | LoD 3 + Building height + Tree properties | LoD 3 + Building archetype | LoD 3 + Agent-based | LoD 3 + Submeter end-use data | 10 m | Daily/hourly |

*Note: Each parameter is assigned a colour palate to differentiate from the table, and the hues of the colour become darker as the LoD increases for the datasets concluded in each parameter to map and assess the UHIE.*

## Discussion

To conclude the proposed FFP framework, a sample purpose of developing the heat action plan has been discussed in detail with the recommended UHIE assessment framework and their suitable LoD characterization for the required datasets. However, the proposed LoDs can be seen as the optimum range and can be modified as per the study context.

### Methodology for mapping and assessment of UHIE- to develop the heat action plan

Urban heat island0 is a complex environmental phenomenon. Therefore, to investigate the UHIE and draw a correlation among the major contributors requires a multi-level and systematic approach considering the meso, local, micro level, and even some time at the plot or building level attributes to develop a comprehensive heat action plan or guidelines for extreme heat adaptation for the cities to adapt. Assessing the surface and the canopy level UHI intensity is also recommended to achieve more nuanced inferences for the studied urban region. A sample framework to map and assess UHIE has been detailed in Table 6.

*Table 6: Recommended framework for UHIE assessment- to develop the Heat Action Plan*

| **UHI types** | **Spatial Scale of Assessment** | | **Key Objective** | **Key study variable** |
|---|---|---|---|---|
| SUHI | Meso scale (region/city) ~ upto10's km | | 1. Mapping and assessment of present and future hotspots | Land surface temperature |
| CLUHI | Local-scale (neighbourhood) 1 to <10 km | Micro-scale (block/street) 1 to 100's m | 2. Mapping of isopleth | Meteorological (Air temperature, Relative humidity) |
| | | | 3. Assessment of Outdoor thermal comfort | Thermal comfort indices (MRT, UTCI, PET, PMV) |

### Required datasets and level of details (LoDs)

To facilitate the purpose of developing the heat action plan, the required data sets for the UHIE assessment according to their LODs are selected as per the three specific objectives mentioned in Figure 3 to conduct the surface (SUHI) and canopy layer UHI (CLUHI) assessment. These LoDs will allow a suitable trade-off to match the application case attributes of the project. The most suitable LoDs for each purpose will enable us to scale up the modelling and assessment exercise with more granular data to achieve higher accuracy with minimal effort.

Extending the fit-for-purpose methodology, we have summarized the most suitable LoDs for each purpose (illustrated in Figure 4). It is aimed to enable the practitioners and decision-makers to further synthesize them by the ideal combinations of any of these datasets across all the recommended LoDs according to their available resources and desired outcomes. It will also help scale the study with all the constraints in each context for respective Indian cities. Moreover, in Table 7, we have also summarized the UHIE assessment methodology (e.g., data collection and mapping, analysis, and validation) along with their recommended spatial assessment scale against each purpose and their respective objectives, as concluded in the proposed FFP framework.

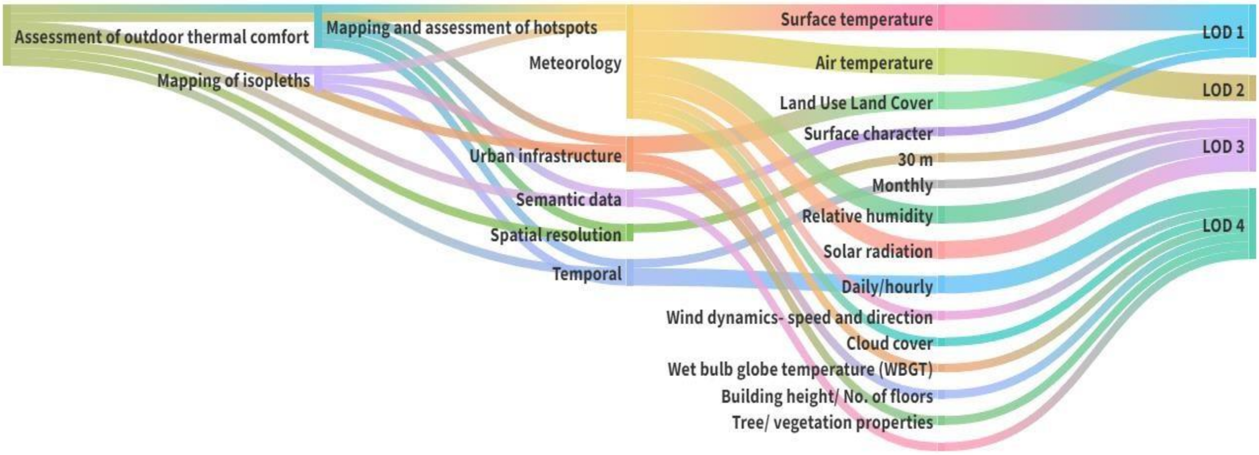

*Figure 3: Sankey diagram showing the critical datasets and their most suitable LOD for developing the HAP*

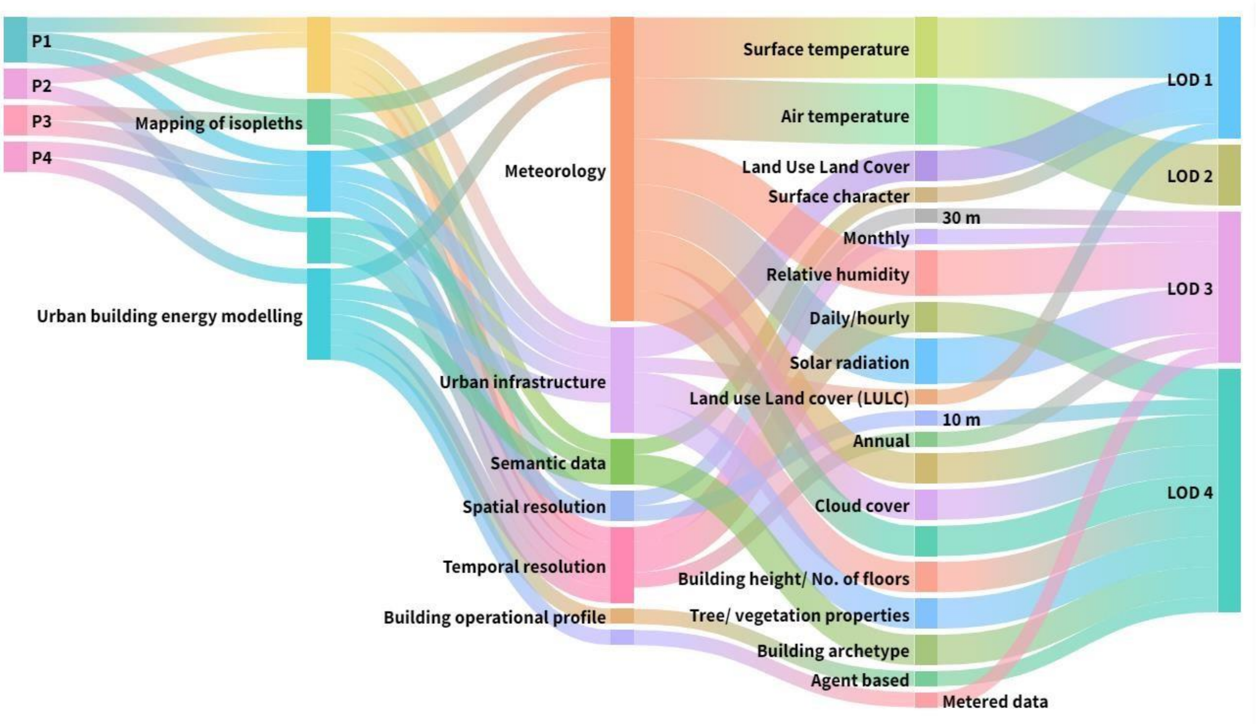

*Figure 4: Sankey diagram summarizing the four key purposes adopted in the proposed FFP framework*

*[Note: P1- Development of Heat Action Plan, P2- Assessing the impact due to urban planning, P3- Improving the outdoor thermal comfort, P4- Reducing the GHG emission]*

*Table 7: Summary of UHIE assessment for the four purposes adopted in the proposed FFP framework*

| **Purpose** | **Objective** | **UHI type** | **Spatial scale of assessment** | **Methodology** | | |
|---|---|---|---|---|---|---|
| | | | | **Data collection and mapping** | **Analysis** | **Validation** |
| SP1 | a. Mapping of Hotspots | SUHI | Meso | Remote sensing | Statistical models | |
| | b. Mapping of Isopleth | CLUHI | Local and/ Micro | Field survey, ArcGIS (interpolation) | ---- | ---- |
| | c. Determining Outdoor thermal comfort | | | --- | Urban Microclimate modelling | Statistical models |
| P2 | a. Mapping of LULC | ----- | Meso | Remote sensing | Statistical models | |
| | b. Mapping of Hotspots | SUHI | | | | |

| | | | | |
|---|---|---|---|---|
| P3 | Refer to the details of CLUHI assessments of P1 (Development of Heat Action Plan) | | | |
| P4 | a. Refer to the details of CLUHI assessments of P1 (Development of Heat Action Plan) | | | |
| | b. Estimate and forecast urban energy use and GHG emission | ------ | Meso and/ Local | Urban Building Energy Modelling (UBEM) |

## Recommendation

As a way forward with the proposed FFP framework, the level of resources against each purpose (e.g., instrumentation/ data, manpower- expertise, and timeline) have been further mapped in this LoD-based FFP framework could be one of a kind to be adopted in India, helping cities evaluate their context and provide evidence-based solutions on the same platform considering the pressing threat due to heat waves and UHIE at the national level.

Table 8 shows the level of resources matrix according to the level of detail. This matrix will help us select the most suitable LoD and customize the overall methodology for UHIE study in any Indian city. Considering the complexity of each purpose, the data acquisition or instrumentation techniques are very critical as they involve the in-situ measurements of metadata along with other datasets (e.g., semantic, urban infrastructure, energy use, etc.) which require a high level of accuracy, high-end tools/instruments, periodic calibration to maintain the consistency, finer resolution of spatial grids across the studied region and continuous monitoring at the hourly interval at times. Mapping and analysis of the data also need precise granularity to model the appropriate boundary condition, which is time-consuming, costly, and requires higher expertise to perform and obtain the desired results with enhanced reliability.

For example, considering the purpose of the 'Development of Heat Action Plan' (P1) and 'Reduction in GHG emissions' (P4), in the case of instrumentation/data, LoD3 requires a medium level for P1 while a very high level of resources are needed for P4. Moreover, if we look at the timeline, considering LoD2, it needs a shorter timeframe for P1 and a longer period for P4 to conclude the study. This matrix will enable the decision-makers to efficiently manage and optimize the resources for a desired outcome.

This LoD-based FFP framework could be one of a kind to be adopted in India, helping cities evaluate their context and provide evidence-based solutions on the same platform considering the pressing threat due to heat waves and UHIE at the national level.

*Table 8: Level of resources matrix- a tool to customize the FFP for efficient decision-making*

| **Level of Resources** | **Instrumentation / Data** | | | | **Manpower - Expertise** | | | | **Timeline** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Level of Details | LoD1 | LoD2 | LoD3 | LoD4 | LoD1 | LoD2 | LoD3 | LoD4 | LoD1 | LoD2 | LoD3 | LoD4 |
| Development of Heat Action Plan | 🟨 | 🟧 | 🟧 | 🟥 | 🟨 | 🟨 | 🟨 | 🟧 | 🟨 | 🟨 | 🟧 | 🟧 |
| Impact due to Urban Planning | 🟨 | 🟧 | 🟥 | 🟥 | 🟨 | 🟧 | 🟥 | 🟫 | 🟨 | 🟧 | 🟧 | 🟥 |
| Improving Outdoor thermal comfort | 🟨 | 🟧 | 🟫 | ⬛ | 🟨 | 🟥 | 🟫 | ⬛ | 🟧 | 🟥 | 🟫 | ⬛ |
| Reduction in GHG emissions | 🟨 | 🟥 | 🟫 | ⬛ | 🟨 | 🟫 | ⬛ | ⬛ | 🟧 | 🟥 | 🟥 | ⬛ |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 🟨 | Low | 🟧 | Medium | 🟥 | High | 🟫 | Very High | ⬛ | Mandatory |

## References

[1] P. Ellis and Mark Roberts, Managing spatial transformation for prosperity and livability. 2016. https://doi.org/10.1596/978-1-4648-0662-9

[2] H. Howe, World Economic Outlook. 2017.

[3] S. Dwivedi et al., "India's climate research agenda : 2030 and beyond Events," 2023.

[4] A. Srivastava, M. Mohapatra, and N. Kumar, "Hot weather hazard analysis over India," Sci. Rep., pp. 1-15, 2022, doi: 10.1038/s41598-022-24065-0. https://doi.org/10.1038/s41598-022-24065-0

[5] Priyadarsini Rajagopalan, "Urban heat island and mitigation in tropical India," 2021, pp. 183-203. https://doi.org/10.1007/978-981-33-4050-3_9

[6] Ahmedabad Municipal Corporation, "Heat action plan guide to extreme heat planning in Ahmedabad, India," 2018.

[7] NRDC, "Expanding heat resilience across India : Heat action plan," 2022.

[8] NDMA, "National guidelines for preparation of action plan - Prevention and management of heat wave." 2019.

[9] IMD, "Heat wave warning services." 2021.

[10] IMD, "Current temperature status and heat wave warning," no. Annexure 1, 2023.

[11] M. Goswami, "What's the weather going to 'Feel Like'? IMD heat index will tell you just that," 2023. [Online]. Available: https://www.thequint.com/explainers/imd-real-feel-factor-weather-forecasts-heat-index-heatwaves#read-more.

[12] NIUA and MOHUA, "An advisory on preparation of heat maps for cities."

[13] MOHUA and URDPFI, "URDPFI Guidelines - 2016," 2016. [Online]. Available: http://mohua.gov.in/link/urdpfi-guidelines.php.

[14] P. A. Mirzaei and F. Haghighat, "Approaches to study Urban Heat Island - Abilities and limitations," Build. Environ., vol. 45, no. 10, pp. 2192-2201, 2010. https://doi.org/10.1016/j.buildenv.2010.04.001

[15] H. Huo et al., "Simulation of the urban space thermal environment based on computational fluid dynamics: A comprehensive review," Sensors, vol. 21, no. 20, pp. 1-27, 2021. https://doi.org/10.3390/s21206898

[16] S. W. Kim and R. D. Brown, "Urban heat island (UHI) intensity and magnitude estimations: A systematic literature review," Sci. Total Environ., vol. 779, p. 146389, 2021. https://doi.org/10.1016/j.scitotenv.2021.146389

[17] Prof Rajan Rawal, Urban Building Energy Modelling - Developing a model for Ahmedabad with Prof Rajan Rawal. 2023.

[18] E. H. Salal Rajan and L. R. Amirtham, "Impact of building regulations on the perceived outdoor thermal comfort in the mixed use neighbourhood of Chennai," Front. Archit. Res., vol. 10, no. 1, pp. 148-163, 2021. https://doi.org/10.1016/j.foar.2020.09.002

[19] R. Kotharkar and A. Bagade, "Local Climate Zone classification for Indian cities: A case study of Nagpur," Urban Clim., vol. 24, pp. 369-392, 2018. https://doi.org/10.1016/j.uclim.2017.03.003

[20] Q. Meng, L. Zhang, Z. Sun, F. Meng, L. Wang, and Y. Sun, "Characterizing spatial and temporal trends of surface urban heat island effect in an urban main built-up area: A 12-year case study in Beijing, China," Remote Sens. Environ., vol. 204, no. November 2016, pp. 826-837, 2018. https://doi.org/10.1016/j.rse.2017.09.019

[21] L. Yao, T. Li, M. Xu, and Y. Xu, "How the landscape features of urban green space impact seasonal land surface temperatures at a city-block-scale: An urban heat island study in Beijing, China," Urban For. Urban Green., vol. 52, no. March, p. 126704, 2020. https://doi.org/10.1016/j.ufug.2020.126704

[22] H. Liu, Q. Zhan, C. Yang, and J. Wang, "Characterizing the spatio-temporal pattern of land surface temperature through time series clustering: Based on the latent pattern and morphology," Remote Sens., vol. 10, no. 4, 2018. https://doi.org/10.3390/rs10040654

[23] 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 Obs. Geoinf., vol. 51, pp. 76-90, 2016. https://doi.org/10.1016/j.jag.2016.05.004

[24] J. Song, S. Du, X. Feng, and L. Guo, "The relationships between landscape compositions and land surface temperature: Quantifying their resolution sensitivity with spatial regression models," Landsc. Urban Plan., vol. 123, pp. 145-157, 2014. https://doi.org/10.1016/j.landurbplan.2013.11.014

[25] A. Mathew, S. Khandelwal, and N. Kaul, "Investigating spatial and seasonal variations of urban heat island effect over Jaipur city and its relationship with vegetation, urbanization and elevation parameters," Sustain. Cities Soc., vol. 35, pp. 157-177, 2017. https://doi.org/10.1016/j.scs.2017.07.013

[26] W. Y. Shih, S. Ahmad, Y. C. Chen, T. P. Lin, and L. Mabon, "Spatial relationship between land development pattern and intra-urban thermal variations in Taipei," Sustain. Cities Soc., vol. 62, p. 102415, 2020. https://doi.org/10.1016/j.scs.2020.102415

[27] Z. Wang, M. Liu, X. Liu, Y. Meng, L. Zhu, and Y. Rong, "Spatio-temporal evolution of surface urban heat islands in the Chang-Zhu-Tan urban agglomeration," Phys. Chem. Earth, vol. 117, no. March, p. 102865, 2020. https://doi.org/10.1016/j.pce.2020.102865

[28] R. Kesavan, M. Muthian, K. Sudalaimuthu, S. Sundarsingh, and S. Krishnan, "ARIMA modeling for forecasting land surface temperature and determination of urban heat island using remote sensing techniques for Chennai city, India," Arab. J. Geosci., vol. 14, no. 11, 2021. https://doi.org/10.1007/s12517-021-07351-5

[29] K. Dutta, D. Basu, and S. Agrawal, "Synergetic interaction between spatial land cover dynamics and expanding urban heat islands," Environ. Monit. Assess., vol. 193, no. 4, pp. 1-22, 2021. https://doi.org/10.1007/s10661-021-08969-4

[30] N. Kikon, P. Singh, S. K. Singh, and A. Vyas, "Assessment of urban heat islands (UHI) of Noida City, India using multitemporal satellite data," Sustain. Cities Soc., vol. 22, pp. 19-28, 2016. https://doi.org/10.1016/j.scs.2016.01.005

[31] J. Quan, Y. Chen, W. Zhan, J. Wang, J. Voogt, and M. Wang, "Multi-temporal trajectory of the urban heat island centroid in Beijing, China based on a Gaussian volume model," Remote Sens. Environ., vol. 149, pp. 33-46, 2014. https://doi.org/10.1016/j.rse.2014.03.037

[32] B. Budhiraja, G. Agrawal, and P. Pathak, "Urban heat island effect of a polynuclear megacity Delhi - Compactness and thermal evaluation of four sub-cities," Urban Clim., vol. 32, no. March, p. 100634, 2020. https://doi.org/10.1016/j.uclim.2020.100634

[33] S. Zheng, J. Guldmann, Z. Liu, and L. Zhao, "Influence of trees on the outdoor thermal environment in subtropical areas: An experimental study in Guang Zhou, China," Sustain. Cities Soc., 2018. https://doi.org/10.1016/j.scs.2018.07.025

[34] M. Salinitro, A. Alessandrini, A. Zappi, and A. Tassoni, "Impact of climate change and urban development on the flora of a southern European city : analysis of biodiversity change over a 120-year period," no. June, pp. 1-10, 2019. https://doi.org/10.1038/s41598-019-46005-1

[35] A. C. Petri, B. Wilson, and A. Koeser, "Land Use Policy Planning the urban forest : Adding microclimate simulation to the planner's toolkit," Land use policy, vol. 88, no. July, p. 104117, 2019. https://doi.org/10.1016/j.landusepol.2019.104117

[36] L. R. Amirtham, "Urbanization and its impact on urban heat island intensity in Chennai Metropolitan Area, India," Indian J. Sci. Technol., vol. 9, no. 5, 2016. https://doi.org/10.17485/ijst/2016/v9i5/87201

[37] A. Chatzidimitriou and S. Yannas, "Microclimate development in open urban spaces: The influence of form and materials," Energy Build., vol. 108, pp. 156-174, 2015. https://doi.org/10.1016/j.enbuild.2015.08.048

[38] F. Cotana et al., "Albedo control as an effective strategy to tackle Global Warming: A case study," Appl. Energy, vol. 130, pp. 641-647, 2014. https://doi.org/10.1016/j.apenergy.2014.02.065

[39] R. Kotharkar, A. Bagade, and P. R. Singh, "A systematic approach for urban heat island mitigation strategies in critical local climate zones of an Indian city," Urban Clim., vol. 34, no. February, p. 100701, 2020. https://doi.org/10.1016/j.uclim.2020.100701

[40] L. Carlosena, Á. Ruiz-Pardo, J. Feng, O. Irulegi, R. J. Hernández-Minguillón, and M. Santamouris, "On the energy potential of daytime radiative cooling for urban heat island mitigation," Sol. Energy, vol. 208, no. July, pp. 430-444, 2020. https://doi.org/10.1016/j.solener.2020.08.015

[41] D. Kannamma and D. A. M. Sundaram, "Significance of microclimatic study in urban canyons towards ambient urban space design," J. Today'S Ideas - Tomorrow'S Technol., vol. 3, no. 1, pp. 95-109, 2015. https://doi.org/10.15415/jotitt.2015.31007

[42] M. Mohan, A. P. Sati, and S. Bhati, "Urban sprawl during five decadal periods over National Capital Region of India: Impact on urban heat island and thermal comfort," Urban Clim., vol. 33, no. October 2019, p. 100647, 2020. https://doi.org/10.1016/j.uclim.2020.100647

[43] H. Farhadi, M. Faizi, and H. Sanaieian, "Mitigating the urban heat island in a residential area in Tehran: Investigating the role of vegetation, materials, and orientation of buildings," Sustain. Cities Soc., vol. 46, p. 101448, 2019. https://doi.org/10.1016/j.scs.2019.101448

[44] B. J. He, L. Ding, and D. Prasad, "Relationships among local-scale urban morphology, urban ventilation, urban heat island and outdoor thermal comfort under sea breeze influence," Sustain. Cities Soc., vol. 60, p. 102289, 2020. https://doi.org/10.1016/j.scs.2020.102289

[45] C. Yan, Q. Guo, H. Li, L. Li, and G. Y. Qiu, "Quantifying the cooling effect of urban vegetation by mobile traverse method: A local-scale urban heat island study in a subtropical megacity," Build. Environ., p. 106541, 2019. https://doi.org/10.1016/j.buildenv.2019.106541

[46] M. Roth, "Urban Heat Islands," 2013.

[47] M. Roth and W. T. L. Chow, "A historical review and assessment of urban heat island research in Singapore," vol. 33, pp. 381-397, 2012. https://doi.org/10.1111/sjtg.12003

[48] X. Huang and Y. Wang, "Investigating the effects of 3D urban morphology on the surface urban heat island effect in urban functional zones using high-resolution remote sensing data: A case study of Wuhan, Central China," ISPRS J. Photogramm. Remote Sens., vol. 152, no. April, pp. 119-131, 2019. https://doi.org/10.1016/j.isprsjprs.2019.04.010

[49] M. Karimimoshaver, R. Khalvandi, and M. Khalvandi, "The effect of urban morphology on heat accumulation in urban street canyons and mitigation approach," Sustain. Cities Soc., vol. 73, no. March, p. 103127, 2021. https://doi.org/10.1016/j.scs.2021.103127

[50] W. Liao, T. Hong, and Y. Heo, "Energy & Buildings The effect of spatial heterogeneity in urban morphology on surface urban heat islands," Energy Build., vol. 244, p. 111027, 2021. https://doi.org/10.1016/j.enbuild.2021.111027

[51] J. Litardo et al., "Urban Heat Island intensity and buildings' energy needs in Duran, Ecuador: Simulation studies and proposal of mitigation strategies," Sustain. Cities Soc., vol. 62, no. July, p. 102387, 2020. https://doi.org/10.1016/j.scs.2020.102387

[52] K. Gunawardena, T. Kershaw, and K. Steemers, "Simulation pathway for estimating heat island influence on urban/suburban building space-conditioning loads and response to facade material changes," Build. Environ., vol. 150, pp. 195-205, 2019. https://doi.org/10.1016/j.buildenv.2019.01.006

[53] J. Parker, "The Leeds urban heat island and its implications for energy use and thermal comfort," Energy Build., p. 110636, 2020. https://doi.org/10.1016/j.enbuild.2020.110636

[54] S. Duan, Z. Luo, X. Yang, and Y. Li, "The impact of building operations on urban heat / cool islands under urban densification : A comparison between naturally-ventilated and air-conditioned buildings," Appl. Energy, vol. 235, no. July 2018, pp. 129-138, 2019. https://doi.org/10.1016/j.apenergy.2018.10.108

[55] R. Kumar, V. Mishra, J. Buzan, R. Kumar, D. Shindell, and M. Huber, "Dominant control of agriculture and irrigation on urban heat island in India," Sci. Rep., vol. 7, no. 1, pp. 1-10, 2017. https://doi.org/10.1038/s41598-017-14213-2

[56] P. P. Wong, P. Lai, C. Low, S. Chen, and M. Hart, "The impact of environmental and human factors on urban heat and microclimate variability," Build. Environ., vol. 95, pp. 199-208, 2016. https://doi.org/10.1016/j.buildenv.2015.09.024

[57] H. Yan, V. A. Vorontsov, and D. Dye, "Intermetallics Alloying effects in polycrystalline g strengthened Co e Al e W base alloys," vol. 48, pp. 44-53, 2014. https://doi.org/10.1016/j.intermet.2013.10.022

[58] H. Jin, P. Cui, N. H. Wong, and M. Ignatius, "Assessing the effects of urban morphology parameters on microclimate in Singapore to control the urban heat island effect," Sustain., vol. 10, no. 1, 2018. https://doi.org/10.3390/su10010206

[59] E. Jamei, P. Rajagopalan, M. Seyedmahmoudian, and Y. Jamei, "Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort," Renew. Sustain. Energy Rev., vol. 54, pp. 1002-1017, 2016. https://doi.org/10.1016/j.rser.2015.10.104

[60] L. Huang, J. Li, D. Zhao, and J. Zhu, "A fieldwork study on the diurnal changes of urban microclimate in four types of ground cover and urban heat island of Nanjing, China," Build. Environ., vol. 43, no. 1, pp. 7-17, 2008. https://doi.org/10.1016/j.buildenv.2006.11.025

[61] B. Chun and J. M. Guldmann, "Impact of greening on the urban heat island: Seasonal variations and mitigation strategies," Comput. Environ. Urban Syst., vol. 71, no. September 2017, pp. 165-176, 2018. https://doi.org/10.1016/j.compenvurbsys.2018.05.006

[62] F. Yang and L. Chen, "Developing a thermal atlas for climate-responsive urban design based on empirical modeling and urban morphological analysis," Energy Build., vol. 111, pp. 120-130, 2016. https://doi.org/10.1016/j.enbuild.2015.11.047

[63] Y. Shi, K. K. L. Lau, C. Ren, and E. Ng, "Evaluating the local climate zone classification in high density heterogeneous urban environment using mobile measurement," Urban Clim., vol. 25, no. July, pp. 167-186, 2018. https://doi.org/10.1016/j.uclim.2018.07.001

[64] T. Holderness, S. Barr, R. Dawson, and J. Hall, "An evaluation of thermal Earth observation for characterizing urban heatwave event dynamics using the urban heat island intensity metric," Int. J. Remote Sens., vol. 34, no. 3, pp. 864-884, 2013. https://doi.org/10.1080/01431161.2012.714505

[65] L. Liu et al., "An integrated local climatic evaluation system for green sustainable eco-city construction: A case study in Shenzhen, China," Build. Environ., vol. 114, pp. 82-95, 2017. https://doi.org/10.1016/j.buildenv.2016.12.018

[66] G. S. N. V. K. S. N. Swamy, S. M. Nagendra, and U. Schlink, "Impact of urban heat island on meteorology and air quality at microenvironments," J. Air Waste Manag. Assoc., vol. 0, no. 0, pp. 876-891, 2020. https://doi.org/10.1080/10962247.2020.1783390

[67] M. Mohan et al., "Industrial heat island: a case study of Angul-Talcher region in India," Theor. Appl. Climatol., vol. 141, no. 1-2, pp. 229-246, 2020. https://doi.org/10.1007/s00704-020-03181-9

[68] R. Kotharkar, A. Bagade, and A. Ramesh, "Assessing urban drivers of canopy layer urban heat island: A numerical modeling approach," Landsc. Urban Plan., vol. 190, no. May, p. 103586, 2019. https://doi.org/10.1016/j.landurbplan.2019.05.017

[69] A. Jeganathan, R. Andimuthu, R. Prasannavenkatesh, and D. S. Kumar, "Spatial variation of temperature and indicative of the urban heat island in Chennai Metropolitan Area, India," Theor. Appl. Climatol., vol. 123, no. 1-2, pp. 83-95, 2016. https://doi.org/10.1007/s00704-014-1331-8

[70] N. Yadav, C. Sharma, S. K. Peshin, and R. Masiwal, "Study of intra-city urban heat island intensity and its influence on atmospheric chemistry and energy consumption in Delhi," Sustain. Cities Soc., vol. 32, no. April, pp. 202-211, 2017. https://doi.org/10.1016/j.scs.2017.04.003

[71] S. Bhati and M. Mohan, "WRF-urban canopy model evaluation for the assessment of heat island and thermal comfort over an urban airshed in India under varying land use/land cover conditions," Geosci. Lett., vol. 5, no. 1, 2018. https://doi.org/10.1186/s40562-018-0126-7

[72] S. Bhati and M. Mohan, "WRF model evaluation for the urban heat island assessment under varying land use/land cover and reference site conditions," 2015. https://doi.org/10.1007/s00704-015-1589-5

[73] S. Kedia, S. P. Bhakare, A. K. Dwivedi, S. Islam, and A. Kaginalkar, "Estimates of change in surface meteorology and urban heat island over northwest India: Impact of urbanization," Urban Clim., vol. 36, no. January, p. 100782, 2021. https://doi.org/10.1016/j.uclim.2021.100782

[74] A. Cortes, A. Jesfel, J. Ace, and A. Blanco, "Evaluating mitigation strategies for urban heat island in Mandaue City using ENVI-met," J. Urban Manag., vol. 11, no. 1, pp. 97-106, 2022. https://doi.org/10.1016/j.jum.2022.01.002

[75] R. N. Faragallah and R. A. Ragheb, "Evaluation of thermal comfort and urban heat island through cool paving materials using ENVI-Met," Ain Shams Eng. J., vol. 13, no. 3, p. 101609, 2022. https://doi.org/10.1016/j.asej.2021.10.004

[76] A. Albatayneh, D. Alterman, and A. Page, "Adaptation the use of CFD modelling for building thermal simulation," ACM Int. Conf. Proceeding Ser., pp. 68-72, 2018. https://doi.org/10.1145/3178461.3178466

[77] R. Padmanaban, A. K. Bhowmik, and P. Cabral, "Satellite image fusion to detect changing surface permeability and emerging urban heat islands in a fast-growing city," PLoS One, vol. 14, no. 1, pp. 1-20, 2019. https://doi.org/10.1371/journal.pone.0208949

[78] T. van Hooff, B. Blocken, and Y. Tominaga, "On the accuracy of CFD simulations of cross-ventilation flow for a generic isolated building: Comparison of RANS, LES, and experiments," Build. Environ., vol. 114, pp. 148-165, 2017. https://doi.org/10.1016/j.buildenv.2016.12.019

[79] N. Antoniou, H. Montazeri, M. Neophytou, and B. Blocken, "CFD simulation of urban microclimate: Validation using highresolution field measurements," Sci. Total Environ., vol. 695, p. 133743, 2019. https://doi.org/10.1016/j.scitotenv.2019.133743

[80] S. Murakami, S. Kato, and T. Kim, "Indoor climate design based on CFD Coupled simulation of convection, radiation, and HVAC control for attaining a given PMV value," Build. Environ., vol. 36, no. 6, pp. 701-709, 2001. https://doi.org/10.1016/S0360-1323(00)00069-X

[81] P. Piroozmand, G. Mussetti, J. Allegrini, M. H. Mohammadi, E. Akrami, and J. Carmeliet, "Coupled CFD framework with mesoscale urban climate model: Application to microscale urban flows with weak synoptic forcing," J. Wind Eng. Ind. Aerodyn., vol. 197, no. August 2019, p. 104059, 2020. https://doi.org/10.1016/j.jweia.2019.104059

[82] S. Saneinejad, P. Moonen, T. Defraeye, D. Derome, and J. Carmeliet, "Coupled CFD, radiation and porous media transport model for evaluating evaporative cooling in an urban environment," J. Wind Eng. Ind. Aerodyn., vol. 104-106, pp. 455-463, 2012. https://doi.org/10.1016/j.jweia.2012.02.006

[83] Q. Wang, C. Zhang, C. Ren, J. Hang, and Y. Li, "Urban heat island circulations over the Beijing-Tianjin region under calm and fair conditions," Build. Environ., vol. 180, p. 107063, 2020. https://doi.org/10.1016/j.buildenv.2020.107063

[84] J. Bernard, M. Musy, I. Calmet, E. Bocher, and P. Keravec, "Urban heat island temporal and spatial variations: Empirical modeling from geographical and meteorological data," Build. Environ., vol. 125, pp. 423-438, 2017. https://doi.org/10.1016/j.buildenv.2017.08.009

[85] C. Ketterer and A. Matzarakis, "Comparison of different methods for the assessment of the urban heat island in Stuttgart, Germany," Int. J. Biometeorol., vol. 59, no. 9, pp. 1299-1309, 2015. https://doi.org/10.1007/s00484-014-0940-3

[86] B. G. Heusinkveld, G. J. Steeneveld, L. W. A. van Hove, C. M. J. Jacobs, and A. A. M. Holtslag, "Spatial variability of the Rotterdam urban heat island as influenced by urban land use," J. Geophys. Res., vol. 119, pp. 2966-2989, 2014. https://doi.org/10.1002/2012JD019399

[87] C. Beck et al., "Air temperature characteristics of local climate zones in the Augsburg urban area (Bavaria, southern Germany) under varying synoptic conditions," Urban Clim., vol. 25, no. April, pp. 152-166, 2018. https://doi.org/10.1016/j.uclim.2018.04.007

[88] M. K. Firozjaei, M. Kiavarz, S. K. Alavipanah, T. Lakes, and S. Qureshi, "Monitoring and forecasting heat island intensity through multi-temporal image analysis and cellular automata-Markov chain modelling: A case of Babol city, Iran," Ecol. Indic., vol. 91, no. July 2017, pp. 155-170, 2018. https://doi.org/10.1016/j.ecolind.2018.03.052

[89] 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. https://doi.org/10.1016/j.rse.2011.07.003

[90] C. Yin, M. Yuan, Y. Lu, Y. Huang, and Y. Liu, "Effects of urban form on the urban heat island effect based on the spatial regression model," Sci. Total Environ., vol. 634, pp. 696-704, 2018. https://doi.org/10.1016/j.scitotenv.2018.03.350

[91] Q. Weng, D. Lu, and J. Schubring, "Estimation of land surface temperature-vegetation abundance relationship for urban heat island studies," Remote Sens. Environ., vol. 89, no. 4, pp. 467-483, 2004. https://doi.org/10.1016/j.rse.2003.11.005

[92] H. C. Ho, A. Knudby, P. Sirovyak, Y. Xu, M. Hodul, and S. B. Henderson, "Mapping maximum urban air temperature on hot summer days," Remote Sens. Environ., vol. 154, pp. 38-45, 2014. https://doi.org/10.1016/j.rse.2014.08.012

[93] C. Berger, J. Rosentreter, M. Voltersen, C. Baumgart, C. Schmullius, and S. Hese, "Spatio-temporal analysis of the relationship between 2D/3D urban site characteristics and land surface temperature," Remote Sens. Environ., vol. 193, pp. 225-243, 2017. https://doi.org/10.1016/j.rse.2017.02.020

[94] Y. Hu, Z. Dai, and J. Guldmann, "Modeling the impact of 2D / 3D urban indicators on the urban heat island over different seasons : A boosted regression tree approach," J. Environ. Manage., vol. 266, no. 11, p. 110424, 2020. https://doi.org/10.1016/j.jenvman.2020.110424

[95] M. M. Baby and G. Arya, "A Study of Urban Heat Island and Its Mapping," International J. Sci. Eng. Res., vol. 4, no. 3, pp. 45-47, 2016.

[96] M. Mohan, Y. Kikegawa, B. R. Gurjar, S. Bhati, and N. R. Kolli, "Assessment of urban heat island effect for different land use-land cover from micrometeorological measurements and remote sensing data for megacity Delhi," Theor. Appl. Climatol., vol. 112, no. 3-4, pp. 647-658, 2013. https://doi.org/10.1007/s00704-012-0758-z

[97] R. Neog et al., "An infrared thermography-based study on the variation in diurnal and seasonal land surface temperature at Dibrugarh city, India," model. Earth Syst. Environ., vol. 6, no. 4, pp. 2047-2061, 2020. https://doi.org/10.1007/s40808-020-00772-3

[98] M. Musy and A. Bernabe, "Radiative properties of the urban fabric derived from surface form analysis : A simplified solar balance model," vol. 122, pp. 156-168, 2015. https://doi.org/10.1016/j.solener.2015.08.031