An assessment of the universal thermal climate index of urban outdoor spaces - a case study of Central Business District (CBD), Ahmedabad

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Abstract

This study is conducted to assess the transition in outdoor thermal comfort (OTC) due to the synergistic effects of high-density high-rise development in urban regions and increasing global temperature. The shifting climate of urban spaces impacts Outdoor thermal comfort(OTC), thus human behaviour and accessibility to outdoor spaces. Central Business District(CBD), located in the centre of a growing metro city, Ahmedabad, in a hot and dry climate, is the case study site. The on-site measurement and simulation method has been adopted to analyze the microclimate condition for current and future development scenarios of 2050 with increased Floor area ratio(FAR) and tree cover. To understand and quantify the heat stress on the human body produced by the surrounding meteorological circumstances, the Universal Thermal Climate Index (UTCI) has been used. The on-site collected data and simulation results provide a basis for studying the physiological and physical attributes related to OTC. The results suggest a significant impact of the sky view factor and the role of mean radiant temperature on OTC in all development scenarios. The shading due to the increased height of building stock imparts a favourable impact on thermal stress in outdoor urban areas.

Keywords - Outdoor Thermal comfort, Universal Thermal Climate Index, Urban Heat Island, Microclimate, ENVI-met.

1. Introduction

The rapid expansion of urban construction, accompanied by an increase in global temperature, is changing the environment of urban regions globally. In India, the urban population amounts to 461 million people, and due to rapid urbanization, it is growing by 2.3% each year. By 2050, it is projected that India will have added 416 million urban dwellers. This urban infrastructure growth demands a holistic urban development strategy and creates an opportunity to design human centric policies with the consideration of climate change. In the Indian urban setup, outdoor spaces are important to a sustainable city as they are the spaces that link the public with the urban built context while accommodating daily pedestrian traffic and various outdoor activities. When the outdoor thermal comfort is favourable, people are more inclined to use outdoor spaces. A comfortable outdoor environment reflects on indoor environments, reducing energy demand and pollutant concentration inside buildings (Kasun Perera, Marc Schnabel, 2015)[1].

Taleghani, Sailor, and Ban-Weiss (2016) have reviewed different heat mitigation strategies for OTC in which the authors have found out the use of vegetation (parks, street trees, green roofs, and green walls) and high albedo material (White reflective roofs, reflective ground pavements) as heat mitigation strategies for sustainable development. The assessment of increasing floor area ratio (FAR) allows an understanding of the influence of urban geometry and densification on outdoor thermal comfort and urban heat island effects. This study aims to evaluate the current outdoor thermal comfort of the central business district (CBD), Ahmedabad, with the help of the universal thermal climate index (UTCI) and assessment of future projections of the Universal thermal climate index (UTCI) in conjunction with the increasing built-up area and green cover with changing weather conditions.

The physical and physiological characteristics help to assess static and objective aspects of OTC. The physical level considers the interaction of the human body with the surrounding environment, which can be studied with field measurement and modelling the microclimate data like Air temperature, Relative humidity, wind speed, and solar radiation. The physiological level study focuses on the thermoregulatory response of the human body toward the surrounding thermal environment. Different thermal comfort indices like PMV, PET, SET, and UTCI help to understand this aspect of outdoor thermal comfort (Chng saun Fong, Nasrin Aghamohammadi, et al., 2019)[2]. In tropical climates like India, PET and UTCI are more suitable indices for evaluating OTC (Mahua Mukherjee, Shatabdi Mahanta, 2014)[3]. Compared to other thermal comfort indices, UTCI is very sensitive to variations in ambient stimuli like temperature, solar radiation, humidity, and especially wind speed and can represent the human body's response (Krzysztof Blazejczyk, Yoram Epstein. et al., 2011)[4], which makes UTCI suitable thermal comfort indices for OTC study.

In various studies related to OTC with the help of UTCI, researchers adopted several methods and tools: (a) using existing meteorological data to calculate and establish a trend in UTCI, (b) on-site microclimate monitoring for calculating and predicting UTCI based on the context (c) Modelling and simulating mean radiant temperature and other microclimate parameters for calculating UTCI for present and future prediction. Evola, G., Magri, C., et al., 2019[5] adopted a hybrid method combining on-site measurement with simulation tools. Where on-site data collection was used to validate and find the gap between simulated microclimate and UTCI data with actual data. As the mean radiant temperature is a crucial parameter while calculating UTCI and in the OTC study, it depends upon the context and the LoD of the model used for simulation. By comparing on-site data with the simulation results provides the accuracy of the model and allows calibration.

2. Methods

The methodology for this study has been divided into two parts: (a)Field Measurement and (b) Simulation– modelling. The steps followed: (1) Site selection (2) On-site field measurement and data collection (3) Development scenario and weather prediction (4) Modelling and simulation (5) Accuracy check of the model with the help of onsite collected data (6) UTCI assessment.

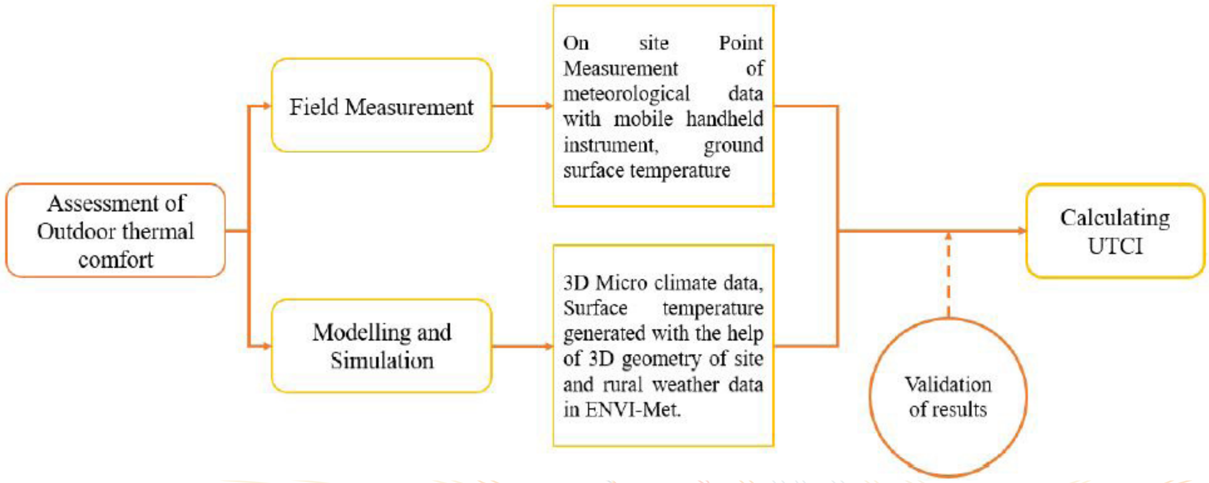


Figure 1: Basic framework of the workflow for the methodology

2.1 Site selection

Ahmedabad is one of the fastest-growing cities in the world (Forbes Magazine,2022), with innovative and progressive development strategies. The Ahmedabad Municipal Corporation (AMC) and the Ahmedabad Urban Development Authority (AUDA), along with HCP architects and planners, have been tackling rapid urbanization by transforming the city center into a vibrant Central business district (CBD), allowing an increase in the Floor Space Index (FSI) from the current 1.8 to 5.4 in the coming decades. Central Business District (CBD), located alongside the river Sabarmati, comprises 927 buildings with a 1.33 km^2 site area, including commercial, health care, institutional and residential buildings. This Scenario gives an ideal situation to study the impact of increasing urbanization on Outdoor thermal comfort in hot and dry climates.

To better understand the correlation between Urban geometry and OTC, eight spots have been selected within the site area. Each spot has distinct contexts, like tree cover, soft/hardscape, street-to-building height ratios, and water bodies. The selection of these eight spots has different sky view factors and represents various ambient conditions of any urban landscape. This spot will give a holistic scenario of CBD.

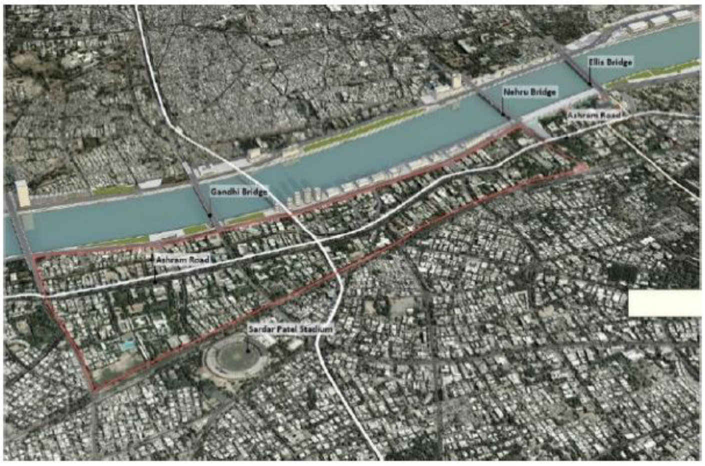


Figure 2: Central Business district, Ahmedabad with major landmarks

Table 1: Proposed urban development scheme for CBD

Parameter	Existing	Future
FAR (Plot)	1.8	5.4
FAR (Gross)	1	5
Total Built Up Area	1275000 m^2	5400000 m^2
Population	85000	200000
Street Coverage (Public Domain)	22%	40%
Number of blocks	31	76
Average block perimeter	743m	416m
Green Cover in Public Domain	6%	30%

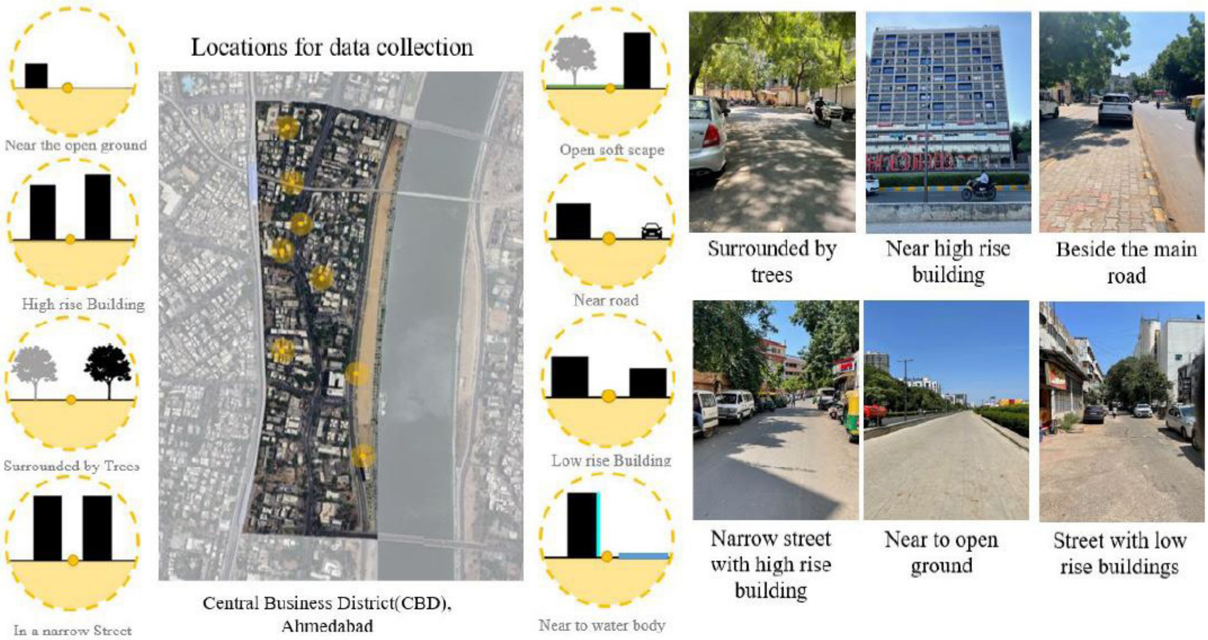


Figure 3: Different spot selected CBD area with various contextual attributes

2.2 Field Measurement

The on-site study aimed to create a database of meteorological factors like air temperature, relative humidity, mean radiant temperature, and wind speed at different times of day and various climatic conditions. Along with this, the surface temperature, On-site observations, sky view factor, and thermographic images have been documented. Weather data from major weather stations of Ahmedabad and weather data from the nearby weather station located on the CEPT University campus have been collected for the same duration to understand variations in the macro and micro climate of the site. This collected data set will help to determine the accuracy and computational sensitivity of microclimate data generated with the help of ENVI-met.

The data collection was conducted during four different time frames: morning at 8:00 am, afternoon at 12:00 am, evening at 4:00 pm, and night at 8:00 pm. These time-frames at the four-hour intervals will give data with different solar azimuth angles, changing the long-wave and short-wave radiation based on the sky view factor (SVF). This exercise has been repeated over a span of 6 months at 15-day intervals from October 2022 to March 2023. This period of the year covers the typical summer and winter seasons. A clear sky is expected and observed during this period of time as ENVI-met does not consider the cloud condition. For this same time frame weather, data has been collected from the nearby weather station, located in the CEPT University (2.5 km from the site), and the major weather station of the city located at the Ahmedabad International Airport (12 km from the site).

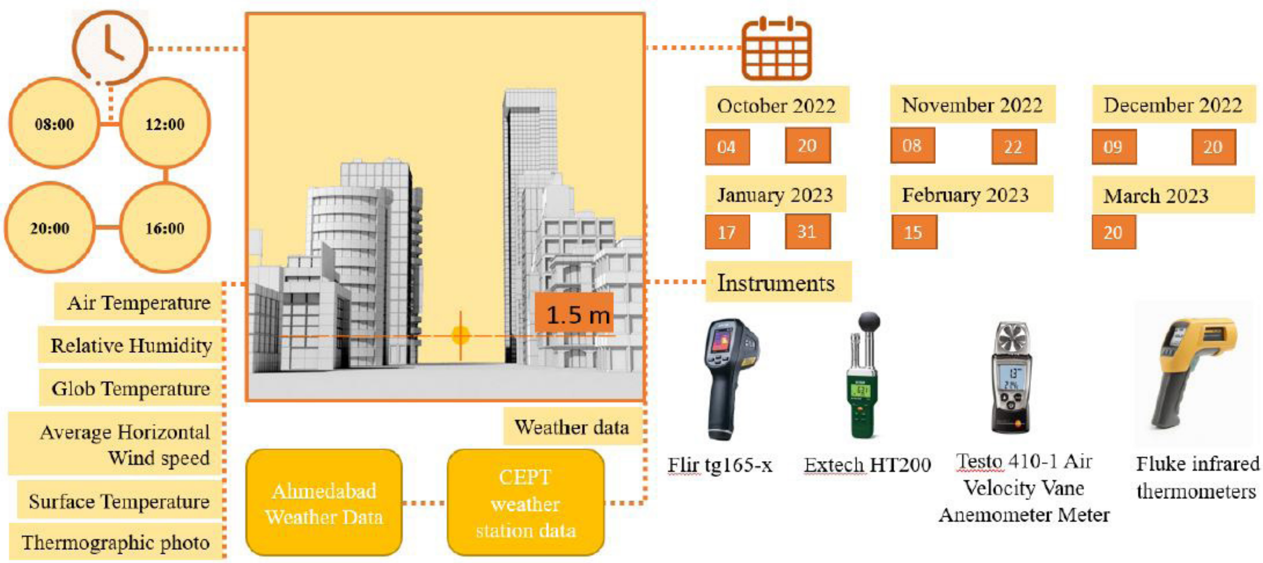


Figure 4: Time period and instruments used in On-site measurements

On-site Air temperature (°C), Mean radiant Temperature (°C), Relative Humidity (%), Surface Temperature (°C), and Wind speed were measured with different instruments at 1.5 m height from ground level. The overall study has been conducted at the pedestrian level, and the same working plane has been selected in the simulation module. Extech HT200 has been used to measure globe Temperature and further calculate mean radiant temperature, Relative humidity, and Air temperature. Wind speed has been measured with the Testo 410-1 Air velocity vane Anemometer in two directions to calculate average horizontal wind speed. 561 Fluke infrared thermometer for surface temperature and Flir TG165-x Thermal Camera for the thermographic image have been used.

2.3 Modelling and Simulation

ENVI-met-5 software has been used for continuous and multi-point data for different scenarios created to study OTC in the CBD area. By providing geometric and semantic data of the CBD area with the weather data file first, microclimate data have been extracted from ENVI-met. Further, with the postprocessing of that data in the Biomet engine of ENVI-met, the UTCI has been calculated. The Leonardo tool from ENVI-met-5 has been used for graphical representation and detailed data extraction from simulation.

2.3.1 Development Scenario

To analyze the change in OTC of CBD area with changing urban morphology, three scenarios have been studied,

(a) Current development scenario of the CBD area
(b) Extreme development scenario Of 2050
(c) Extreme development scenario with Native tree plantation

Table 2: Characteristics of different scenarios selected for the study

Cases	Building Geometry	Envelop	Weather Data	Tree	Land cover and water body
Current development	As per the current development scenario	ECBC baseline	Ahmedabad weather .epw file	As per the existing site Condition	As per the existing site condition
2050 Development	Extreme development scenario with 5.4 FSI proposed plan	ECBC baseline	Morphed .epw file based on IPCC RCP 8.5	As per the current site Condition	As per the existing site condition
2050 development + Native trees	Extreme development scenario with 5.4 FSI proposed plan	ECBC baseline	Morphed .epw file based on IPCC RCP 8.5	As per the GDCR and AUDA guidelines	As per the current site condition

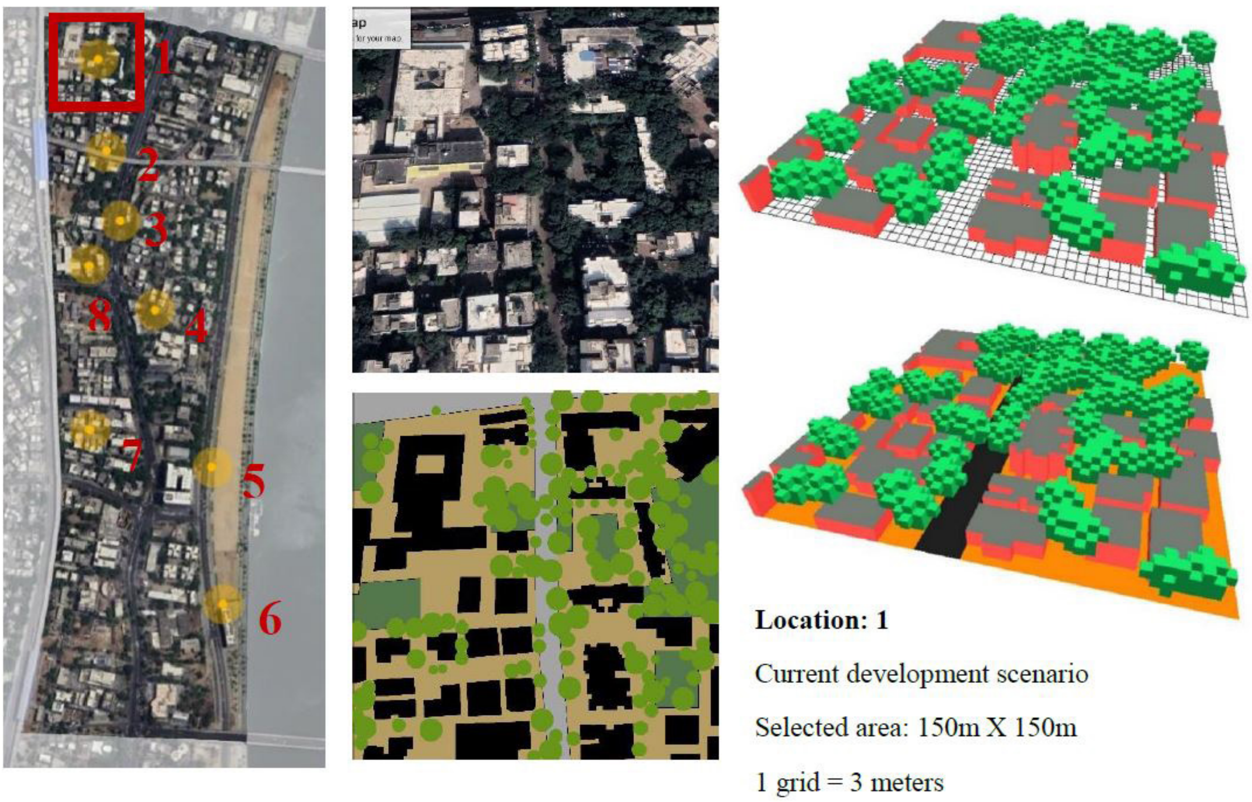


Figure 5: Modelling of location 1 in ENVI-met for current development scenario

2.3.2 Defining the Model Characteristics and Methodology

The site area of 1.33 km^2 with 927 commercial and residential building units (Appendix section 7.4 survey data) has been divided into eight parts based on the location selected for on-site measurements. The exact location of the on-site measurement 150m X 150m area has been selected for simulation.

For the current development scenario, the building geometry is taken from the on-site collected data, site survey data, and previously done research on the CBD area. The model has LoD1 (Level of Detail) with reference to site survey data. The envelope details of all the buildings are as per the ECBC baseline. The ground surface cover and trees are as per the site condition. The future development scenario is considered extreme development, where all the building blocks are considered to be developed with a full possible floor space index (FSI) of 5.4. Based on that, the geometrical and shape file has been prepared. The built environment has been modelled in ENVI-met- spaces with a 3-meter per grid ratio. Standard trees from the ENVI-met library have been used for modelling as per the on-site tree dimensions.

2.3.3 Weather Data

Ahmedabad's most relevant rural weather data file in the context of the case study site has been selected. This .epw file has been used in full forcing mode in ENVI-met for simulating microclimate data. The constant offset method is used to create the future hourly weather data. The Intergovernmental Panel on Climate Change (IPCC) has developed different representative concentration pathways (RCPs) for future climate modelling. The RCPs represent climate scenarios based on greenhouse gas (GHG) emissions in coming years. From that, the RCP8.5 has been used, representing the most carbon-intensive pathway with summer temperatures in high latitudes that will rise by at least 2° C by 2050. On this basis Future, rural TMY files will be generated. This file and the model of the extreme development scenario will be used to simulate the microclimate weather data of the Central Business District (CBD) of 2050.

2.3.4 UTCI Calculation

To analyze the outdoor thermal comfort for all three scenarios for different locations from the CBD area, UTCI has been calculated for two days of the year.

(1) Summer Design Day: 18th May
(2) Winter Design Day: 27th December

These two days will represent the two extreme weather cases in Ahmedabad. The simulation lasted 15 hours, from 6 AM to 8 PM. For the calculation of UTCI, air temperature, mean radiant temperature, relative humidity, and horizontal average wind speed data have been extracted from the ENVI-met simulated microclimate data, and for personal factors, the "Standard Human": ISO 7730 with age - 35, Weight – 75, Height – 1.75 m, Gender – Male, clo value – 0.90, and Met value – 1.48 has been taken. The UTCI value for all the locations and selected days have been calculated at the 1.5 m pedestrian level. The Leonardo tool of ENVI-met has been used for data interpretation and presentation.

2.3 Data Validation

To check the accuracy of the simulated data, data validation is required. Two days representing typical summer and winter days from the experiment dates have been selected to compare the simulation results with the onsite collected data set. For these two days, the weather data from a nearby weather station located at CEPT University have been used for simulating more accurate results. Simulations for 8 AM, 12 PM, 4 PM, and 8 PM have been conducted for 17th January 2023 and 20th October 2022. Microclimate data for the same location have been compared for the same time frame to check the model's accuracy. As the material used in the modelling is not as per the site, variations in the results are expected. With this exercise, the gap between the simulated data and actual data can be estimated. Further, this data can be used to calibrate the simulation model, but in this study, calibration is not part of the scope of the work.

3. Results

3.1 Simulation data validation

To check the accuracy of the simulation model, statistical analysis of on-site collected data and simulated data has been done. The linear regression method has been used. For the air temperature data degree of variation is less with R^2= 0.941 but in the case of mean radiant temperature, there is a gap between on-site data and simulated data as the simulation model has enveloped detail based on ECBC baseline but not similar to on-site condition. The data is from a nearby weather station, but the collected data might be influenced by the microclimate of the location thus, similar trends can be observed. For the UTCI values from the simulation and calculated UTCI value from on-site data, follow the same trend and in linear regression R^2= 0.7246. The data following the same trend while comparing two different scenarios still provide a relevant delta.

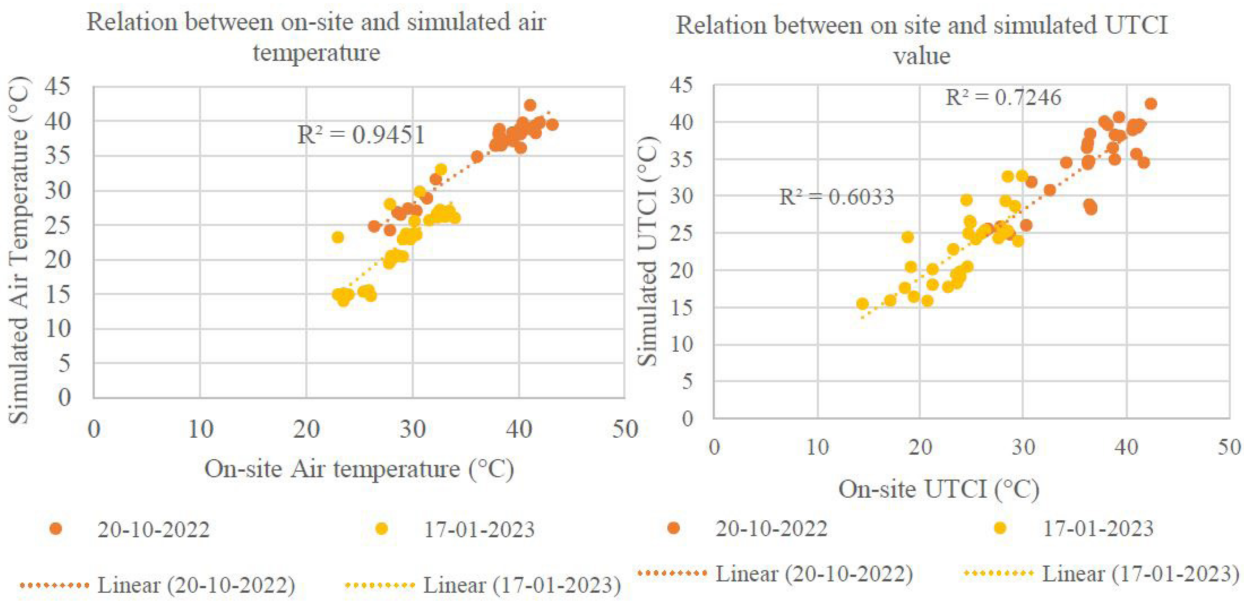
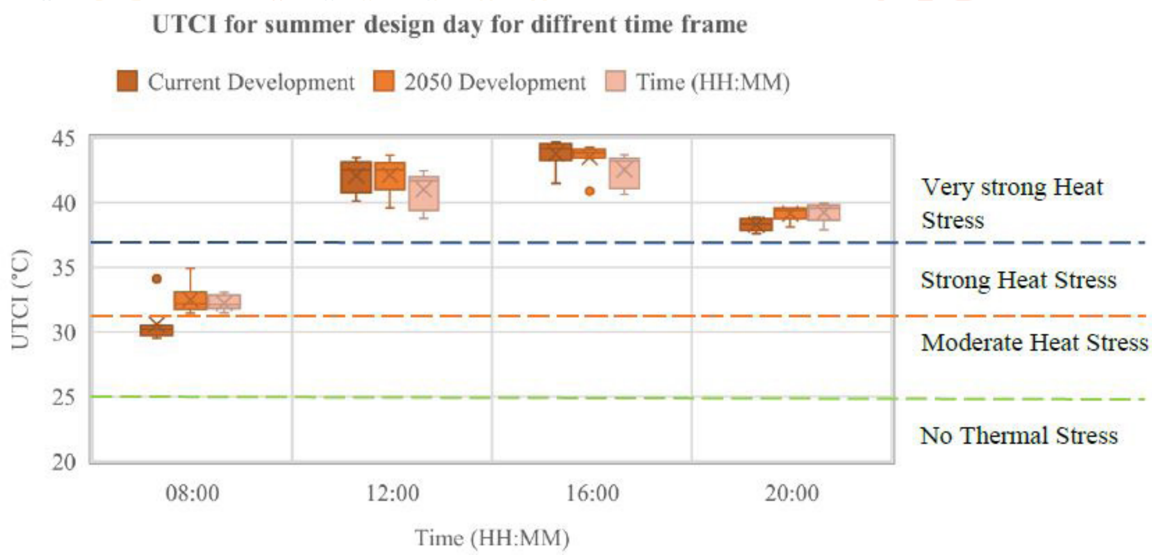


Figure 6: Comparative analysis of On-site collected data and simulated data for (a) Air Temperature (b) UTCI

3.2 Universal Thermal Climate Index (UTCI

In both summer and winter design days, the lower thermal stress level is achieved with more native tree plantation during the daytime. The shading effect of the trees reduces the increase in surface temperature and results in lower MRT. Though the Air temperature is higher for the 2050 development scenario, during the summer design day, less thermal stress can be observed at 12:00 and 16:00 hours. With increased FSI the building height is higher compared to the current development scenario, resulting in mode-shaded hours for the open outdoor space. But during the night time due to the urban heat island effect, the surface temperatures are higher than the current development scenario and give higher UTCI heat stress values. Due to the overall increase in temperature for future development scenarios, a smaller number of hours are falling under the no thermal stress category on winter design day. Even during the winter design day the majority of hours during the daytime fall under moderate heat stress levels.



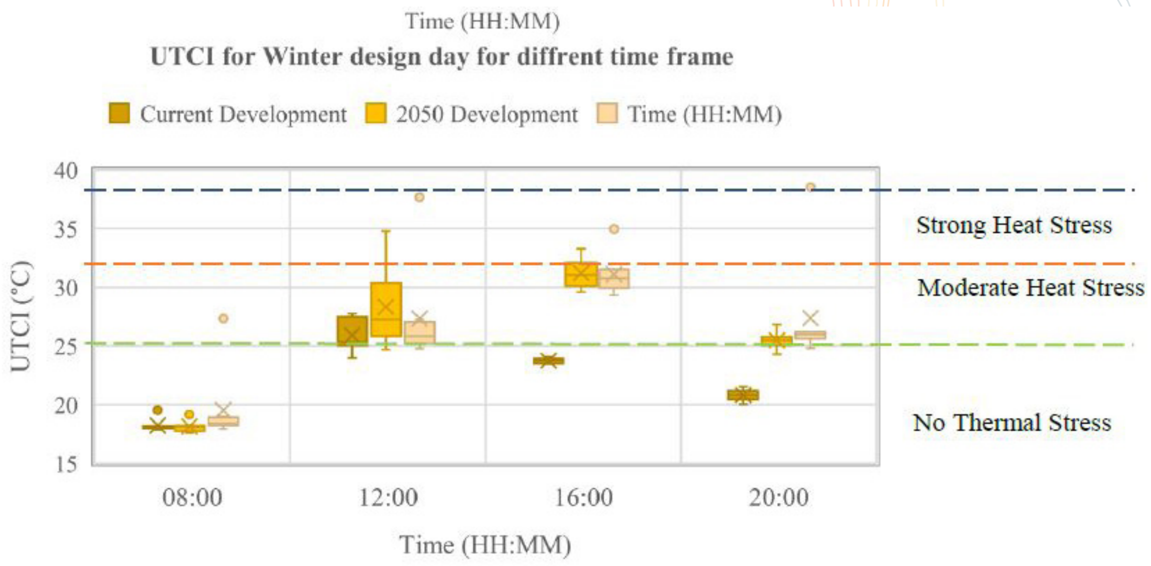


Figure 7: Comparative analysis of UTCI value for all three development scenarios at four time periods on (a) Summer design day (b) Winter design Day

In all three cases, a reduction in heat stress can be observed during the daytime in summer in cases with increased building height and more trees. In the case of location- 4, the reduction delta is lower because the existing site is already shaded with trees. The majority of land cover in location 3 is concrete, which is increasing the heat stress level for both the current development and 2050 development scenario. But when the native tree plantation has been introduced on the edges of roads and pathways, even during the daytime, comparatively less heat stress can be seen. After sunset hours when there is zero solar radiation, due to urban heat island effect (2050 development scenario) it takes more time to cool down resulting in higher heat stress.

4. Conclusion

The study of UTCI for outdoor thermal comfort shows the direct impact of change in contextual attributes as it is susceptible to minute changes in any microclimate stimuli. The predicted thermal conditions for the outdoor spaces of the CBD have a significant number of hours falling in higher thermal stress levels due to increased global temperature. While increased building heights are changing the sky view factor of any given observation point. The shading with increased height of building stock during the daytime plays a favourable role in the overall result of OTC. Tree cover acts as a more efficient factor by providing shading and increasing humidity in hot and dry contexts of the site.

With increasing global temperature, facing higher temperatures in outdoor spaces is inevitable but in this condition during the design process shadow analysis and study of the sky view factor of any outdoor space will help to articulate more thermally comfortable and accessible spaces. Following the minimum requirement of the plantation guidelines for new development and strategies for the green streets with native plants can help to reduce the effect of urban heat islands and achieve lower heat stress levels in urban outdoor places at the pedestrian level. This will improve the quality and accessibility of outdoor urban spaces for a more significant number of hours throughout the year.

Limitation: The envelope detail of the model used for simulation is constant as per ECBC baseline with LoD1 for all the buildings. The lack of surface albedo, surface roughness, and WWR as per the site creates a gap between the on-site microclimate data and simulated data. With a smaller grid size in ENVI-met, more accurate geometry of the building can be created which will give more accurate data for surrounding outdoor space.
Future Scope: In the case of OTC the sky view factor and shading hours play a significant role, further in-depth research for the effect of the sky view factor on different climates and geographical locations can be done.

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6. References

Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., & Tinz, B. (2012). Comparison of UTCI to selected thermal indices. International Journal of Biometeorology, 56(3), 515–535. https://doi.org/10.1007/s00484-011-0453-2

Bröde, P., Błazejczyk, K., Fiala, D., Havenith, G., Holmér, I., Jendritzky, G., Kuklane, K., & Kampmann, B. (2013). The Universal Thermal Climate Index UTCI compared to ergonomics standards for assessing the thermal environment. Industrial Health, 51(1), 16–24. https://doi.org/10.2486/indhealth.2012-0098

Lukić, M., & Milovanović, J. (2020). UTCI-based assessment of urban outdoor thermal comfort in Belgrade, Serbia. Proceedings of the International Scientific Conference - Sinteza 2020.

Zhang, L., Wei, D., Hou, Y., Du, J., Liu, Z., Zhang, G., & Shi, L. (2020). Outdoor thermal comfort of urban park—A case study. Sustainability, 12(5), 1961. https://doi.org/10.3390/su12051961

Evola, G., Naboni, E., Margani, G., & Magri', C. (2020). Modelling outdoor thermal comfort in urban canyons: Presentation and validation of a novel comprehensive workflow. Proceedings of Building Simulation 2019: 16th Conference of IBPSA.

Ayyad, Y. N., & Sharples, S. (2019). Envi-MET validation and sensitivity analysis using field measurements in a hot arid climate. IOP Conference Series. Earth and Environmental Science, 329(1), 012040. https://doi.org/10.1088/17551315/329/1/012040

Zare, S., Hasheminejad, N., Shirvan, H. E., Hemmatjo, R., Sarebanzadeh, K., & Ahmadi, S. (2018). Comparing Universal Thermal Climate Index (UTCI) with selected thermal indices/environmental parameters during 12 months of the year. Weather and Climate Extremes, 19, 49–57. https://doi.org/10.1016/j.wace.2018.01.004

Mijorski, S., Cammelli, S., & Green, J. (2019). A hybrid approach for the assessment of outdoor thermal comfort. Journal of Building Engineering, 22, 147–153. https://doi.org/10.1016/j.jobe.2018.12.003

Coccolo, S., Kämpf, J., Scartezzini, J.-L., & Pearlmutter, D. (2016). Outdoor human comfort and thermal stress: A comprehensive review on models and standards. Urban Climate, 18, 33–57. https://doi.org/10.1016/j.uclim.2016.08.004

Fang, Z., Feng, X., Liu, J., Lin, Z., Mak, C. M., Niu, J., Tse, K.-T., & Xu, X. (2019). Investigation into the differences among several outdoor thermal comfort indices against field surveys in subtropics. Sustainable Cities and Society, 44, 676– 690. https://doi.org/10.1016/j.scs.2018.10.022