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Research Paper

Impact of Changes in Built Mass and Vegetation Cover on the Thermal Environment of Urban Area

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ABSTRACT

Urbanization associated with increasing built footprint and declining green cover is a matter of concern while climate change manifests with increasing earth temperature causing serious threats of heat stress. This is attributed to increasing impervious surfaces and decreasing vegetation cover and water bodies in and around urban areas. There is a need to objectively understand the relationship between changes in the built environment and green cover and the corresponding alteration of the thermal environment so that climate change impacts can be mitigated by appropriate strategies for planning and designing these areas. The present study seeks to empirically evaluate the effect of the changing physical environment on the thermal comfort conditions and resulting micro-climate in an urban area by gathering quantitative evidence of changing temperature profiles. The study is conducted on a 7 acres institutional campus under Sambalpur Municipal Corporation for two time periods to examine the changes in thermal condition with respect to alterations in the built mass and tree cover. The micro-scale scenarios are modelled through simulations using ENVI-met V 4.4.6. with variations of built mass and tree cover, and corresponding thermal maps of the selected area are generated and analysed. Thermal maps show increasing trends of temperature with increasing built mass and reducing tree cover. However, it is observed that in places where green cover is maintained the increase in built mass does not impact the thermal conditions significantly. The results derived have implications for designing climate-sensitive built spaces and appropriate landscaping of the surrounding open spaces to mitigate heat stress and improve micro-climatic conditions.

Keywords *– Built mass, Thermal condition, Tree cover, Micro-climate, Climate change*

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I. Introduction

Climate change associated with rapid urbanization has caused an increase in ambient air temperature and heat stress. Changing landscapes with the densification of built-up areas and degradation of natural areas are found to compound the negative impacts of climate change, and pose additional significant challenges to ecosystem functionality and human well-beingin cities around the world.Urban land use and land cover changes are much discussed and a matter of concern as it impacts the ecology of urban systems and consequently affects the environment (Weith et al., 2020) People and the natural environment are primarily affected in urban areas (White et al., 2005) as cities are engulfed with extreme temperature gradients,when, about half of the human population globally lives in urban areas (United Nations, Department of Economic and Social Affairs, 2014). Large population giants and developing economies like India are susceptible to climate change with growing built infrastructure. According to the United Nations-Habitat's World Cities Report 2022, the urban population of India is projected to be around 675 million in 2035 with 43.2% of the population at mid-year residing in urban areas. Urban areas are experiencing critical environmental challenges, including changes in the thermal environment with global warming and urbanization intensifying the urban heat island effect. The urban thermal environment impacted by anthropogenic processes is intensified further by warmer earth temperatures and increased frequency of extreme events.

The urban microclimate and the outdoor conditions of human comfort is influenced by urban morphology parameters; build infrastructures, vegetation, and surface materials. However, urban green and blue spaces have the potential to counteract these pressures by providing habitats for a range of species (Niemela,1999; Goddard et al. 2010) and a number of environmental and cultural benefits while contributing to climate change adaptation and mitigation(Kabisch et al., 2015; Kabisch et al., 2017).Nature-based solutions (NBS) that involve blue and green spaces enable and simplify implementation actions in urban landscapes by taking intoaccount the ecosystem services provided by nature (Secretariat of the Convention on BiologicalDiversity 2009).Multiplebenefits related to climate change adaptation and mitigation arerecognised to be achieved by the adoption of nature-based approaches in modifying urban landscapes,(Hartig et al. 2014). Increase in urban green spaces may result in better mental and physical health by mitigating heat stress (Keniger et al. 2013). In addition, NBS may, in many cases, present more efficientand cost-effectivesolutions than more traditional technical approaches (EuropeanCommission 2015). Still, evidence-based analysis of their effects, effectiveness forclimate change adaptation and mitigation, and provision of co-benefits are required to enable the implementation of appropriate urban landscape planning and design.The present study seeks to evaluate the effect of the changing morphology on the thermal comfort conditions and resulting micro-climate in an urban area by gathering quantitative evidence of changing temperature profiles.

II. Literature Review

Adaptation to actual or expected climate change effects involves a range of measures or actions that can be taken to reduce the vulnerability of society and to improve the resilience capacity against an expected changing climate. Possible adaptation measures to handle climate change can take many forms and be effective at a range of spatial and temporal scales.Past studies in the context of urban areas have indicated the deterioration of the latent heat flux cooling effect contributed byevapotranspiration from the blue and green land cover.(Ramamurthy & Bou-Zeid, 2015; Yu, et al., 2017; Ige, et al., 2017). Urban thermal environment dynamics and impacts can vary significantly with complex interactions between environmental variables (e.g., wind movement, relative humidity, vapor pressure, and soil properties) (El Kenawy, 2020; He, B.-J., 2018). Furthermore, urban areas alter the albedo and radiation due to the surface qualities of the built environment(Offerle, et al., 2005).

The limited open spaces, the lack of green spaces, the high building density, the compactness of the Urban Blocks, the poor air quality, and the traffic congestion can lead to urban environmental degradation (Makropoulou, 2017). Application of bioclimatic concepts in the built environment, like greening the cities, can be a way to decrease the outdoor temperature during hot days. Increasing green cover improves the microclimate with the improvement of outdoor thermal comfort conditions. The existence of vegetation can contribute to cooling the urban environment through the evapotranspiration process. The shade of tree foliage can also control solar radiation as the incident radiation is absorbed through the photosynthesis process. (Dimoudi, et al., 2003).The augmentation of Urban Green Infrastructure improves the microclimatic conditions by providing a ‘cool island’ effect (Oliveira et al. 2011) and contributesto the global climate effect through the binding of CO2 (Nowak andCrane 2002).Spatial planning of citiesdid not take into account climate change impacts while formulating development guidelines and policies.Urban geometries, building forms, and their envelopes were designed to fulfil functional and visual requirements, rather than to respond to climatic changes. Therefore, it is crucial to develop more sustainable urban areas, that will significantly reduce the carbon footprint of cities.

Long continuous local monitoring records are important to capture temporal climate variability and evaluate the urban thermal environment (Brousse, et al., 2022). For the investigation of small-scale variations, sensors have been established to investigate the impact of built environment in the urban canopy layer (Stewart, 2019). Establishment and operationof high-quality monitoring systemsare often time consuming and expensive, leading to data scarcity. Building heights and orientation, surface materials, vegetation and setting of tree plantation, wind speed and direction at street level that are crucial parameters for investigating urban thermal environments and thermal comfort are often simulated via building-scale models (Van de Walle, 2022). Urban climate processes are assessed by environmental modelling,based on various data sources. The characteristics of urban morphology are extremely important in understanding the urban thermal environment, especially the relationships between Land Use and Land Cover (LULC) and vegetation indices(Ferreira, 2019).Modelling of past and present microclimatic scenarios of urban area is required to comparatively analyzechanging thermal comfort conditions with respect to changes in land use and land cover.Urban climate model simulatingpast urban climate dynamics and future climate development scenarios, can help urban planners to develop effective solutions based on scientific evidence for sustainable urban development (Fallmann, 2020).

III. Methodology

Objective

- To evaluate the urban microclimate by examining the changes in thermal conditions with changing morphology of the area across two time periods
- To compare thermal comfort conditions in different bioclimatic scenarios.

The study focuses on two aspects of the urban space at a micro scale: a) built mass and b) vegetation cover to understand the thermal impacts in the summer month May for the year 2004 and 2022 through microclimatic simulations.

Study area

The study is conducted in the 7 acreacademic complex of Veer Surendra Sai University Campus in Burla. Burla town lies in the composite climatic region of Odisha (Table 1). The selected site has two and three storeyed buildings with good vegetation cover, paved streets and parking areas. The university campus is taken for the study as the morphology of the campus keeps changing with the addition of built mass with the reduction of vegetation cover. The academic complex is used during the daytime when thermal comfort conditions are primarily important. The morphological details of the site are given in Table 2.

Table 1. Geographical Location

Location	Burla
Latitude	21:51
Longitude	83:87
Reference Time Zone	IST (GMT+5:30)
Reference Longitude	75:00

Table 2. Morphological Details

Land Cover (In Acres)	2004	2022
Built-up Area	2.67	3.42
Paved Area	1.24	2.57
Green Cover	11.3	9.22

The built footprints, building materials, and inventory of vegetation on the site are recorded. Trees were categorised according to their height, canopy, Leaf Area Density (LAD), and root depth for modelling on albedo.

Figure 1a and 1b shows the physical profile of the study area in 2004 and 2022. The built mass has increased between the two time periods with the addition of new building blocks and the consequent reduction of vegetation cover.

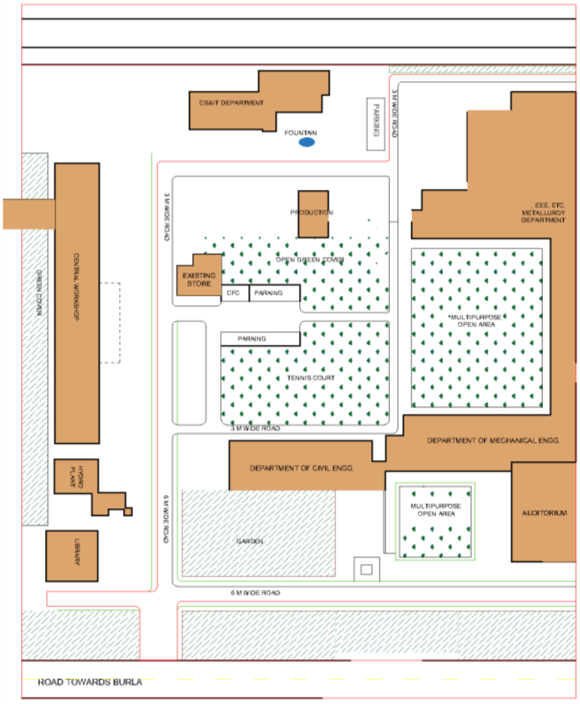


Figure 1a Built Morphology in 2004

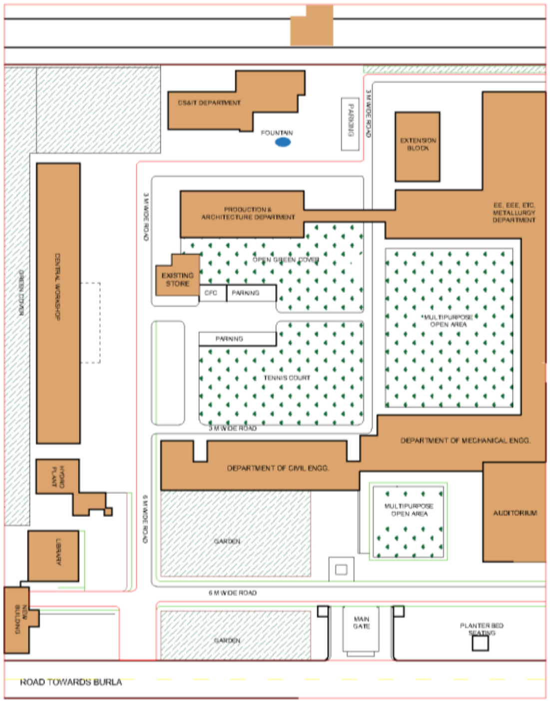


Figure 1b Built Morphology in 2022

Relevant meteorological parameters have been considered in the analysis. The meteorological data taken for conducting the simulation are the hourly temperature, relative humidity, wind speed and wind direction of a typical day during summerfor the year 2004 and 2022.

The methodology includes solving the interactions of temperature, humidity and air movement between air and tree foliage using turbulent fluxes of heat and vapour sub-model. Secondly, the model was used to calculate the interaction of evaporation and transpiration of water from soil through plant that depending by number of stomata and its resistance through leaves. Thirdly, the process of foliage control on net short-wave radiation absorbed by plant that enhanced the course in plant radiation interception was calculated by steady state leaf energy budget sub-model depending on light transmission factor and foliage albedo.

Analysis Tool and Technique

The bioclimatic scenarios were investigated through microclimatic simulations using the micro-scale numerical model, ENVI-met V 4.4.6. ENVI-met simulates the temporal evolution of several thermodynamics parameters on a micro-scale range, creating a 3D (2x2x2 grid cell in meters), non-hydrostatic model of the interactions between building-atmosphere-vegetation (Berardi, et al. 2016). It is a three-dimensional numerical modelcapable of simulating surface-plant-air thermal interactions with a typical resolution of 0.5 to 10m in space, from a single building up to an urban scale, with a maximum of 250 grids.

The model provides specific output to draw conclusions on outdoor thermal comfort.

Firstly, simulation is done with the microclimatic data and then the selected thermal comfort index is estimated through the Predicted Mean Vote (PMV) index.

PMV index evaluates the outdoor thermal comfort and summarizes the impact of the four main atmospheric variables: Air Temperature, Radiative Temperature, Wind Speed and Humidity on the human thermal sensation. Variables referring human characteristics, such as a 35 year old male with 75 kg weight and 1.75 m height, reacting on clothing parameters and body metabolism are taken into account for the calculation of the PMV index (ENVI-met Development Team, 2014)(Table 3). The index values range between -4 (cool conditions) and +4 (hot conditions), while 0 value is characterized as neutral thermal comfort conditions. Sometimes, the indices values can be varying, as the PMV model is based on Fanger (1972) comfort model and relates the energy balance of the human body with the human thermal impression.

Table 3: Personal Parameters

Body Parameters	
Age	35
Gender	Male
Weight (Kg)	75
Height (m)	1.75
Surface Area	1.91 sqm
Clothing Parameters	
Static Clothing Insulation(clo)	0.90
Person's Metabolism	
Total Metabolic Rate (w)	164.49 (=86.21W/sqm)
(met)	1.48

The processes undertaken to model the thermal environment included three main stages: firstly, the organization through the file directory, secondly, modelling and editing the simulation parameters (microclimate data and built elements) using the database of the plants and surface materials creating the area input file (.INX) and the simulation file (.SIM) and finally the assessment of the outcome files (.EDT/.EDX) and their visualization. The flowchart shown in Figure 2 illustrates the processes used in this work in order to perform the simulation with the microclimate parameters.

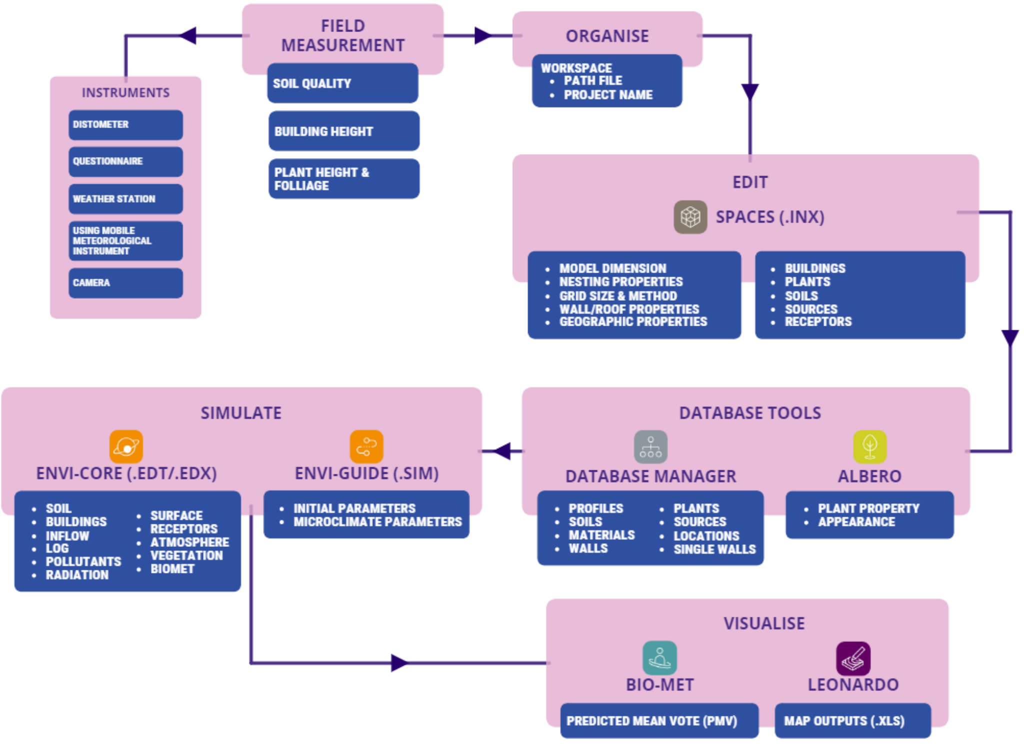


Figure 2 – ENVI-met Work Flow

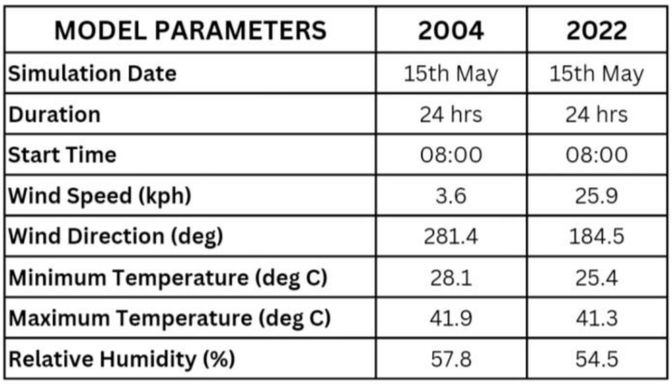
In order to model the area's microclimate conditions and to examine UHI mitigation scenarios, one of the hottest days in 2004 and 2022 was selected. Regarding the peak values of the simulation, the recorded temperature for May was 37.4 °C at 13:00h during summer.The purpose of modelling that area is to examine how vegetation can impact the reduction of local temperature. Soall the main parameters described on Table 4 and Table 5 in the simulation, such as the range of the temperature, humidity, wind speed, the direction of the wind and also the characteristics of the built environment (absorption, reflection, albedo, emissivity of the roads, soil and building materials) remained unchanged, and the effect of the described vegetation scenarios on the urban microclimate is evaluated.

Table 4: Simulation Input Data

Simulation Input Data	
Simulation Model Size (m)	120 x 120 x 60
Model Area (Number of Grids) xyz - Grids60 x 60 x 30	
Size of grid cell (meters)dx, dy,dz2 x 2 x 2	

Geographic location (Latitude, Longitude)	37.96, 23.70
Nesting grids	6
Method of vertical grid generationEquidistant	
dz of the lowest grid box is split into 5 subcells	
Telescoping Factor increases with the height of the building	
Telescoping Factor (%)	25.00
Start Telescoping Factor	18m
Model Rotation out of Grid North	90.00
View point k = 5 i.e 1.5m above ground	
Reference time zone	GMT+2

Table 5: Main Model Parameters



MODEL PARAMETERS	2004	2022
Simulation Date	15th May	15th May
Duration	24 hrs	24 hrs
Start Time	08:00	08:00
Wind Speed (kph)	3.6	25.9
Wind Direction (deg)	281.4	184.5
Minimum Temperature (deg C)	28.1	25.4
Maximum Temperature (deg C)	41.9	41.3
Relative Humidity (%)	57.8	54.5

The ENVI-met model basically consists of a one-dimensional boundary model, that includes vertical profiles of different meteorological parameters up until a height of 2500 meterstelescopic - 25%, buildings height –18 mt. and 5 mt. and a three-dimensional core model that includes all atmosphere, soil, building, and vegetation processes. The 1D boundary model generates one-dimensional profiles for meteorological parameters such as air temperature, specific humidity, and wind vectors (horizontal) for each vertical profile.

The size of the model areas highly depends on the spatial resolution of the model. For that reason, the extent of the total area was modified to fit the grid extent of the basic ENVI-met model. The simulation grid was 60x60 cells horizontally and 30 cells vertically, with cell size 2x2x2 resulting to a total area size of 120x120x60 meters. The simulated total area is about 15.21 acres. This resolution allows analysing small-scale interactions between individual buildings, surfaces and plants for the different scenarios into a period of 24 hours.Each cell is defined by its physical properties of the urban environment, such as surface materials, plants and built infrastructure materials. ENVI-met database managerprovides a variety of materials and 3D plants allowing the detailed reconstruction of accurate modelling of the urban environment. However, in the present study, the trees available in the study area have been modelled in ALBERO and the vegetation database created was loaded onto SPACES in ENVI-MET. Each material type is defined by the specific heat capacity, absorption, transmittance, albedo, and other parameters.Figure 3(a) and 3(b), Table 6 and Table 7 for the built materials and plants illustrate all the selected materials that were used to construct the area model. Figure 3(a) and 3(b) shows that though the campus is characterized by high albedo surfaces (surface materials) the vegetated areas of open space and vegetation cover in the campus is good.

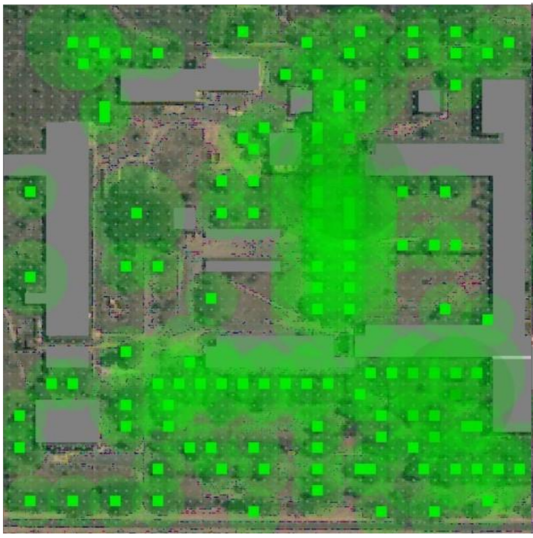


Figure 3a Built footprint and vegetation in 2004

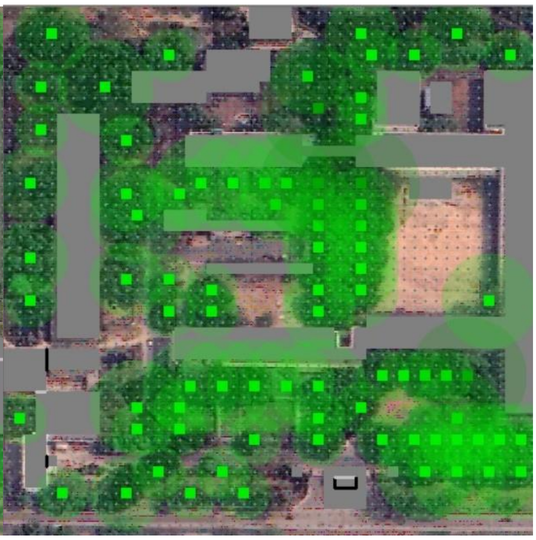
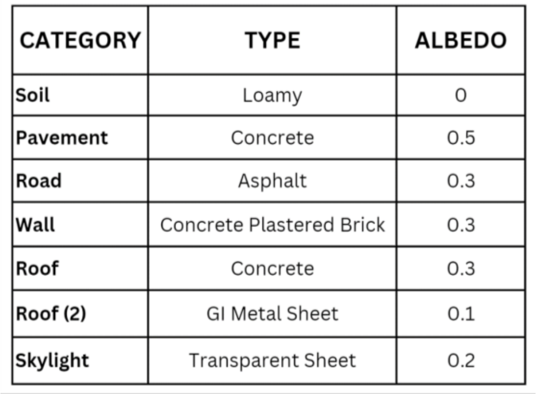


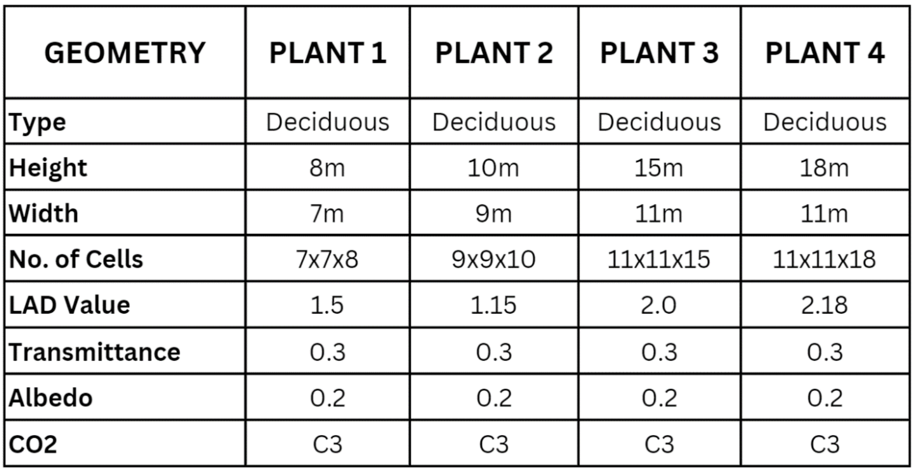
Figure 3b Built footprint and vegetation in 2004

Table 6: Surface Materials



CATEGORY	TYPE	ALBEDO
Soil	Loamy	0
Pavement	Concrete	0.5
Road	Asphalt	0.3
Wall	Concrete Plastered Brick	0.3
Roof	Concrete	0.3
Roof (2)	GI Metal Sheet	0.1
Skylight	Transparent Sheet	0.2

Table 7: Vegetation



GEOMETRY	PLANT 1	PLANT 2	PLANT 3	PLANT 4
Type	Deciduous	Deciduous	Deciduous	Deciduous
Height	8m	10m	15m	18m
Width	7m	9m	11m	11m
No. of Cells	7x7x8	9x9x10	11x11x15	11x11x18
LAD Value	1.5	1.15	2.0	2.18
Transmittance	0.3	0.3	0.3	0.3
Albedo	0.2	0.2	0.2	0.2
CO2	C3	C3	C3	C3

IV. Results

Two different scaled models for two different times 2004 and 2022 with variations in built mass and vegetation cover are analysed to understand the thermal profile of the campus and the microclimate within changing bioclimatic scenarios.

The modelling was done for a peak summer day with highest temperature of 41.9 °C in 2004 and 41.3 °C in 2022. Comparision of the 2D view at 1.5 meter of the air temperature profile models (Figure 4a& Figure 4b) for both the year shows that the maximum air temperature of the microclimate of the campus in 2004 is 22.22 °C and that in 2022 is 24.79 °C and there is a difference of 3.21 °C in the minimum temperature across the two time periods, with higher minimum temperature in 2022. The present status of air temperature of the area (Figure4b)shows that more built mass and albedo surfaces of the campus morphology leads to increasein the ambient air temperature. There is difference of on an average 2.7°C in the temperature gradient of the modelled output between the two years with more temperature in different areas within the campus in 2022.

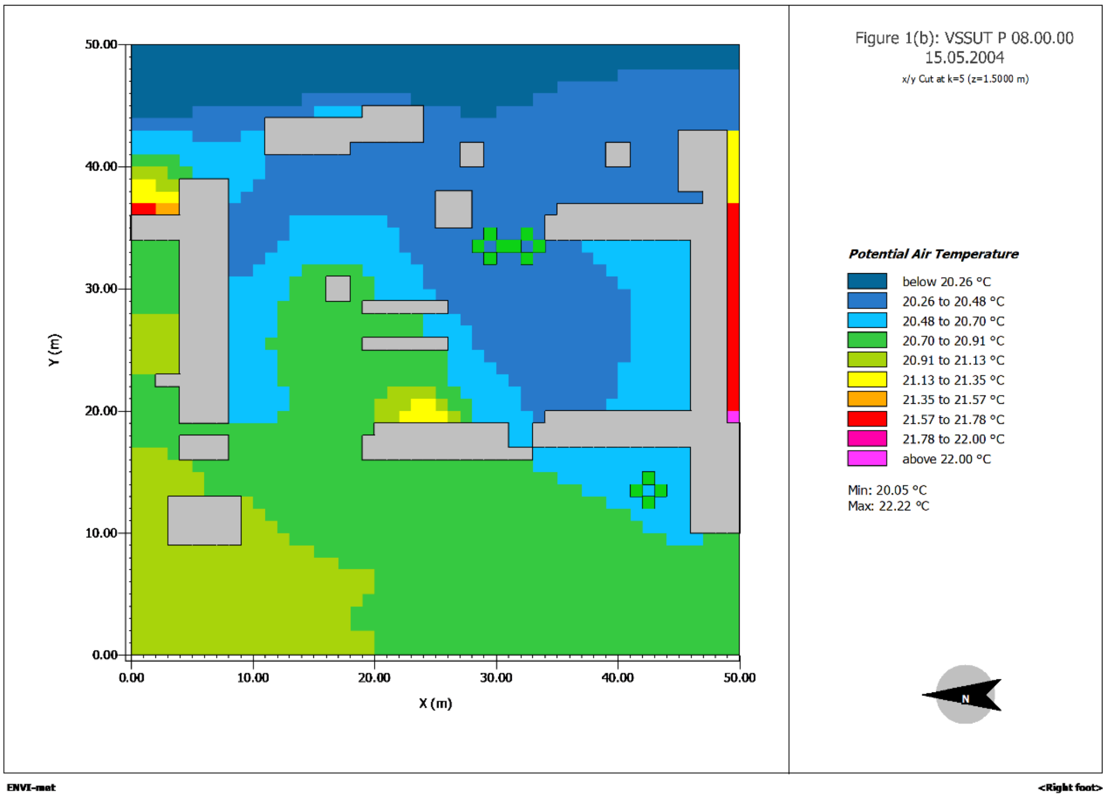


Figure 4a 2D View of the air temperature in the study area in 2004

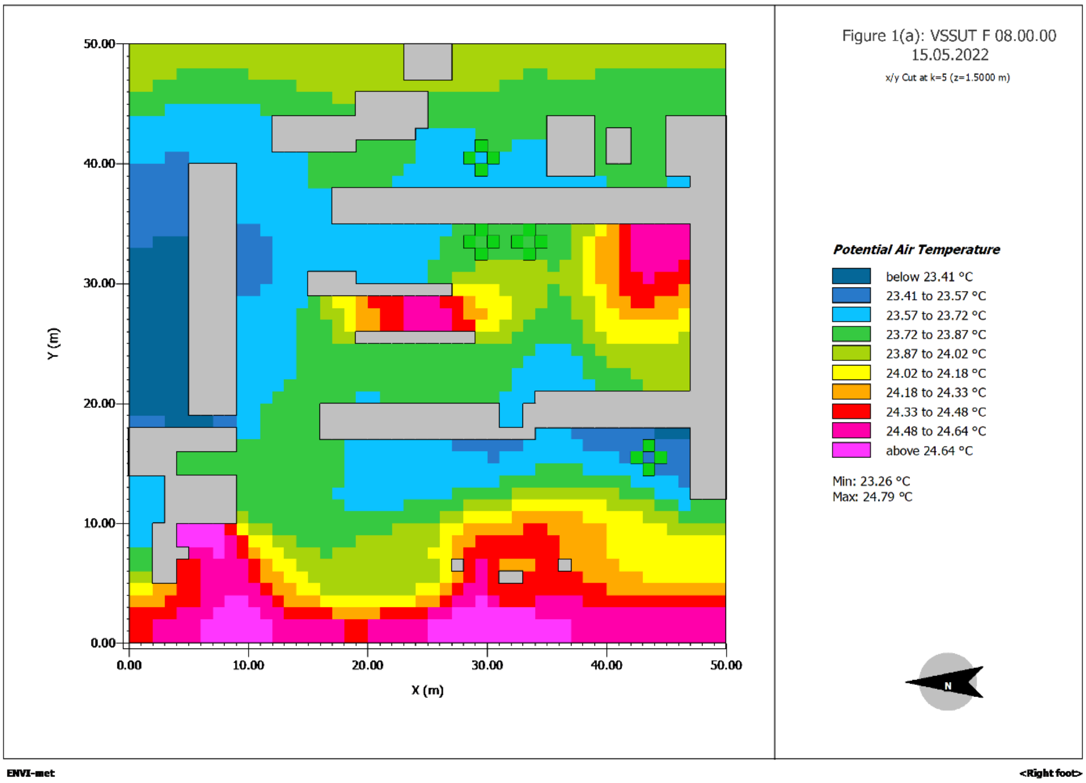


Figure 4b 2D View of the air temperature in the study area in 2022

However, results show that although the input meteorological maximum air temperatures are higher the maximum air temperature within the campus morphology is less due to the presence of a good number of trees inside the campus (Figure 5a &5b). The output shows highertemperaturesalong the western side of the building with no trees and more hard surfaces. Planning trees along the buildings can act as heat mitigation strategy as it is 1.2 degrees cooler near the façade of the buildings having vegetation cover.The simulation results showed that vegetation is characterized as the most effective heat mitigation strategy for the local microclimate.

Figure 5a. 3D Scenario of Vegetation Figure 5b. 3D Scenario of Vegetation
Coverin 2022Cover in 2004

The compared values between the 2004 model and the current condition model of the Predicted Mean Vote (PMV) index are illustrated on Figure 10. The maximum thermal comfort in 2022 is 1.42 on the PMV scale and in 2004 the value is 1.32. The higher value in 2022 is due to the increase in built mass due to the development of the campus. However, favourable thermal comfort conditions exist on the campus even in 2022, with the PMV indexbeing less than 1 in most of the locations due to the existence of good vegetationcover. The estimated PMV at 1.5m height (mean height for human motion) shows improvement of the thermal comfort up to 1 in the PMV scale in the locations with vegetation cover although the built mass has increased. Trees seem to improve the thermal comfort conditions on the campus although the built mass has increased.

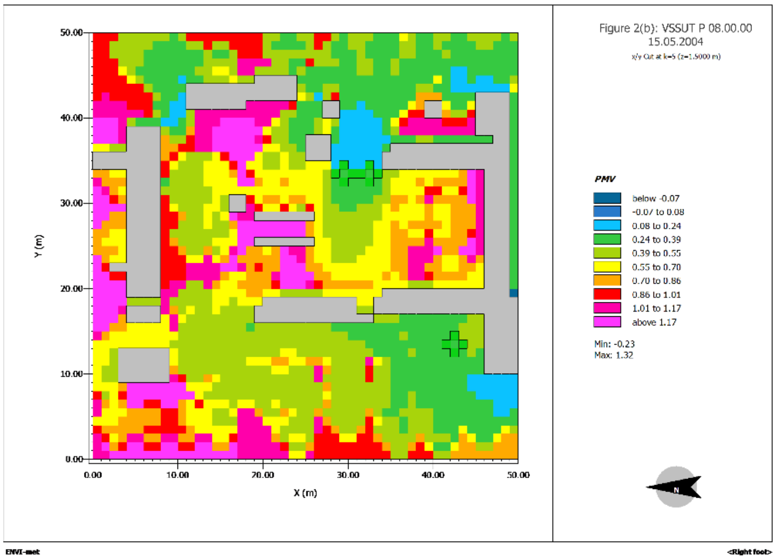


Figure 6a Distribution of thermal comfort values in 2004

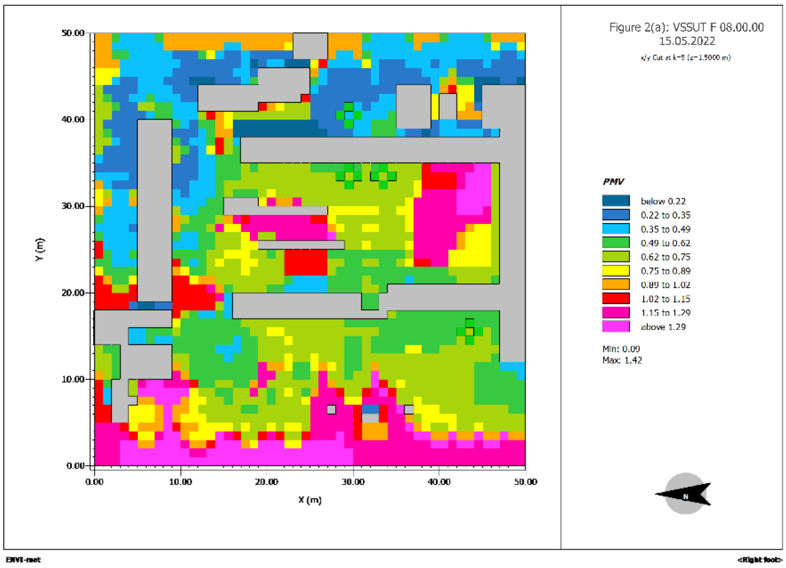


Figure 10 Distribution of thermal comfort values in 2022

V. Conclusion

Considering past urban climate dynamics and future climate development scenarios, urban climate model simulations can support urban planners to develop optimally cost-effective and science-based solutions for sustainable urban development. There is a wide spectrum of models for estimating and describing urban issues on different spatial scales. Different heat mitigation and adaptation strategies have been proposed to minimizethermal stress during summer.

Appropriate planning of vegetation cover is found to provide significant potential to mitigate UHI effects. Analysis of the thermal comfort index proved that the appropriate selection of plant type and planting pattern can contribute to improving the thermal conditions.

For modeling urban climate multi-disciplinary approach of dynamic Spatiotemporal analysis can be applied. There is a scope for further research in bioclimatic concept planning by applying a variety of surface materials with different properties, such as albedo, emission, and absorption rate in combination with different types of trees.

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