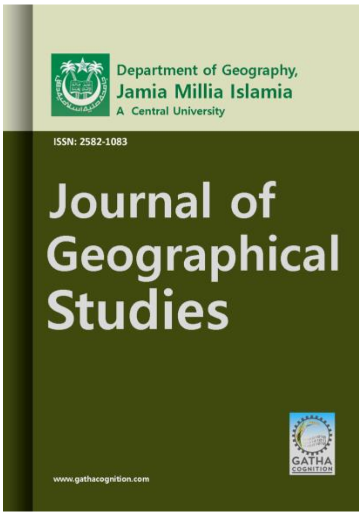

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Original Research Paper

Pune City's Microclimate: An Assessment of Selected Local Climate Zones Using ENVI-Met

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Abstract

The urban fabric of Pune city has undergone massive changes due to diversifying urban functionalities. The study attempts to identify different urban morphological landscapes within the city based on Local Climate Zones (LCZs) configurations. After identification of urban morphology in accordance with the LCZ scheme, the microclimatic simulations for the performance and attenuation of the meteorological parameters that is air temperature (T_a), relative humidity (RH), mean radiant temperature (T_{mrt}), and wind speed (WS) was accomplished through ENVI-met during the warmest month for the city. The urban landscapes characteristics similar to the proposed LCZ configuration and to collect field data for the chosen meteorological parameters ground survey was done. In addition to field observations, climatological normals and long-term trends for the meteorological parameters were also analyzed. The simulation results revealed that barren lands are warmer (by ~18°C) than the compact city core due to the heat sink effect. For T_a and RH the simulation is more reliable in case of open LCZs (R^2~0.9) compared to compact LCZs (R^2~0.5). With changing LCZs, there is no significant change in the simulation except continuous underestimation of the T_{mrt} and the role of wind flow in modifying T_{mrt} was noticed.

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1 INTRODUCTION

Urban morphology and building density play a crucial role in the overall use of energy and promotion of environmental sustainability (Ambrosini *et al*., 2014). Wherever the built-up area increases, the surface area of radiation also increases due to an apparent rise in other radiative surfaces. On the other hand, where the proportion of built-up area to the total area is lower in both vertical and horizontal extent, the radiative heating effect will also be less. Offerle *et al*. (2005) observed that the materials used in urban areas have high thermal capacity, leading to heat flux storage into buildings by day and significant release at night. Thus, built-up areas have a pronounced effect in conditioning city temperatures. The earlier phenomenon is found in the urban areas while the latter is located at the periphery or suburban or village areas. Thus, there is a marked difference between the temperature condition of the urban area and its peripheral zone. This microclimatic effect of excessively warm urban areas than their rural counterparts has been initially confirmed in urban heat island (UHI) studies by Oke (1976) and Owen *et al*. (1998). Later, some research works found that barren open grounds are warmer than the city core (Wang and Yang, 2004; Shah and Ghauri, 2015). This can be attributed to the shading effect of skyscrapers at the urban core.

In his paper, Oke (1976) had vertically classified this UHI effect into the urban canopy and boundary layers. According to him, as the formation of the urban canopy layer depends on the urban morphology, the upper limit of this layer is situated slightly lower to the roof level where the relative spacing between buildings is less. However, it may disappear with increasing relative spacing. The urban boundary layer, which lies above the canopy layer, is a planetary boundary that sets the vertically upper most limit of pollutant. The urban

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canopy was indicated as a micro-scale concept while the other one was denoted as a meso-scale concept by Oke (1976).

Many factors like canyon geometry, thermal properties of used materials, anthropogenic heat, urban greenhouse effect, reduction of evaporating surfaces, etc. affect the urban climate (Santamouris, 2001). Along with temperature and radiation, other weather parameters also get modified and attenuated over urban surfaces (Arnfield, 2003). Studies have also shown that precipitation has effectively increased with urbanization, which can range from 3% to 15% (Santamouris, 2001).

Temperature distribution in the urban areas is highly determined by outgoing long wave radiation and canyon geometry. Buildings and streets absorb the insolation and convert it into sensible heat. All the buildings emit long wave radiation into the sky, mostly from their roofs and walls. The intensity of long wave radiation mostly depends on the area's sky view factor (SVF). Lower the SVF, lower is the spacing between buildings and higher the intensity of long wave radiation. Thus, canyons' air temperature (Ta) is of more interest than the surface temperature.

UHI is only one aspect of climate modification due to urbanization. There are other issues related to the urban microclimate, which vary from one city area to another as well as within a city, manifest as a result of urban morphology on the combination of different weather parameters. Stewart and Oke (2012) in research article titled 'Local climate zones for urban climate studies' have classified local climates based on urban morphology. Stewart and Oke (2012) have aimed to facilitate documentation of site metadata and thereby improve the base of inter-site comparisons. Many of the recent scholars who have worked on urban microclimates have used the classification of Local Climate Zones (LCZ) by Stewart and Oke (2012). For Kochi (Thomas *et al*., 2018), ten such LCZs have been identified. Keeping the factors for delineation of LCZ same as Stewart and Oke (2012) proposed, the suggested value of each of these factors has been regenerated specifically for Kochi. The work has been performed on the primary database. 21 LCZ classes are found in Nagpur including standard 7 built-up types and seven land cover types (Kotharkar and Bagare, 2017). Kotharkar and Bagare (2017) have used LULC maps to identify the land. GIS database based LCZ identification has also been carried out (Zheng *et al*., 2017; Unger *et al*., 2014) where information regarding building, street, topography and land use has been collected in GIS format. Amongst all the parameters suggested for LCZ (Stewart and Oke, 2012), the aspect ratio can be omitted as it depends on the regularity of the street network (Unger *et al*., 2014). World Urban Database and Access Portal Tools (WUDAPT) level 0 method can also be employed for free remote sensing images, mostly as input data (Wang *et al*., 2017). Research shows that the WUDAPT method is useful for meso-scale climate and weather modeling. In contrast, for more precise urban morphology data as an input factor GIS-based method is more useful (Wang *et al*., 2017). A strong correlation has been found between the decrease of T_a and the amount of vegetation in areas where there is no distinct aerial boundary (Wong and Yu, 2005). In a study for Kochi (Thomas *et al*., 2018), the UHI intensity effect is higher during early dawn than early night and also higher in winter than summer. It has been found that by irrigating lawns, cool park island can be formed even in arid cities, which effectively mitigates the UHI effect (Chow *et al*., 2011). Ng *et al*. (2012) found that a properly planned urban greening can also be an efficient method of mitigation of UHI effect. Sky View Factor (SVF) is also an essential factor in the intensification of the UHI effect in urban areas. SVF simply refers to the openness of the sky. By achieving an optimum SVF value the UHI intensification effect can be minimized (Hu *et al*., 2016).

The spatial growth of most Indian cities followed organic development, having a core that is the old city area and is gradually surrounded by newly planned built-up areas (Kotharkar and Bagade, 2017). The conventional organic development of the cities in India too gives rise to the vast differences in the urban morphological structure. Thus the effect of heat island can be seen from a macro-climatic perspective also. Though in cities with colder climates the heat effect can be taken positively, in cities with hot climates it can bring a threat of heat stress (Stewart and Oke, 2012).

Origin and growth of Pune city had a historical past. Kantakumar *et al*. (2016) found out that the speed of urban expansion in the city has doubled from 2001 to 2013 compared to 1992 to 2001. The absolute change is high over the municipal corporation areas while the rate of change is high over the suburban and village jurisdictions (Kantakumar *et al*., 2016). Gohain *et al*. (2021) have shown in their study that there is around 43% increase in built-up area whereas agricultural lands (40.8%), scrubland (37.1%) and fallow lands (22%) have shown a decreasing trend from 1990 to 2019. Hence, it can be inferred that the urban expansion in Pune is taking place at the cost of grasslands, barren lands, and agricultural lands, which also means that urban morphological changes are happening in the city. Studies have also found that such change in land use and land cover has impacted raising the summertime land surface temperature (Gohain *et al*., 2021; Sandbhor *et al*., 2021). Thus, in the present study LCZ (Stewart and Oke, 2012) scheme has been used to identify different microclimates that evolve from the specific urban morphological configuration. Four meteorological variables i.e., Wind Speed (WS), T_a, Relative Humidity (RH) and Mean Radiant Temperature (T_{mrt}) were taken into consideration as these are the most critical factors influencing urban climate. Furthermore, this study will conduct an inter-site comparative analysis if such zones form. There are many softwares like ENVI-met, RayMan, SOLWEIG etc. which have been found to be efficient in simulating thermal comfort and spatial distribution of weather parameters in the city area. In the evaluation of the ENVI-met 4.3 version (Acero and Arrizabalaga, 2018), the simulation output had an excellent correlation with measured values for T_a and RH but weak correlation for T_{mrt}. Thus, in this study a ground-truthing of simulation outputs of version 4.3 has been performed.

1.1 Study Area

For the present study, Pune city (Figure 1) has been chosen which is situated in the western part of Maharashtra state of India. This city falls under the tropical climatic region. Pune is also a growing educational and IT hub of India. Rapid inter-state immigration is taking place which will eventually influence the urban morphology of the city. The identification of LCZ is based on the classification suggested by Stewart and Oke (2012). For the present study some specific areas of Pune city have been chosen to delineate LCZ (Table 1). The choice of areas has been made in such a way that they are spatially well distributed over Pune city. The areas selected for the study are illustrated in Figure 1.

2. METHODOLOGY

2.1 Data Procurement

The meteorological data have been collected from National Data Center (NDC) of India Meteorological Department (IMD), Pune, for the simulation in ENVI-met, for the month of April (1981-2009) which consists of monthly maximum and minimum of T_a and RH, Wind Direction (WD), WS and Global Radiation.

For ground checking of the simulation results of the ENVI-met, field survey was conducted in the 3rd week of April. For collecting weather data, Kestrel Heat Stress Tracker, i.e., a mobile weather station, has been used and for delineation of LCZ, sigma 8 mm fisheye lens has been used to calculate the Sky View Factor (SVF) of selected areas in RayMan pro. For SVF the camera used was Nikon D5100. The camera was mounted over a tripod with a height of 1 meter. Photographs were taken at an aperture of f-8, a shutter speed of 1/100 and ISO 100.

2.2 Calculation of T_{mrt}

T_{mrt} is mainly useful in calculating Physiological Equivalent Temperature (PET). It also takes into account the calculation of the T_a, WS and many other factors. The T_{mrt} cannot be directly calculated in the Kestrel. Thus, the formula given by Thorsson *et al.* (2007) is used for the same with adjusted globe diameter. Many urban climate studies (Lam and Lau, 2018; Crank *et al.*, 2020) which have made use of Kestrel heat stress tracker to estimate T_{mrt}, have used this formula for the calculation.

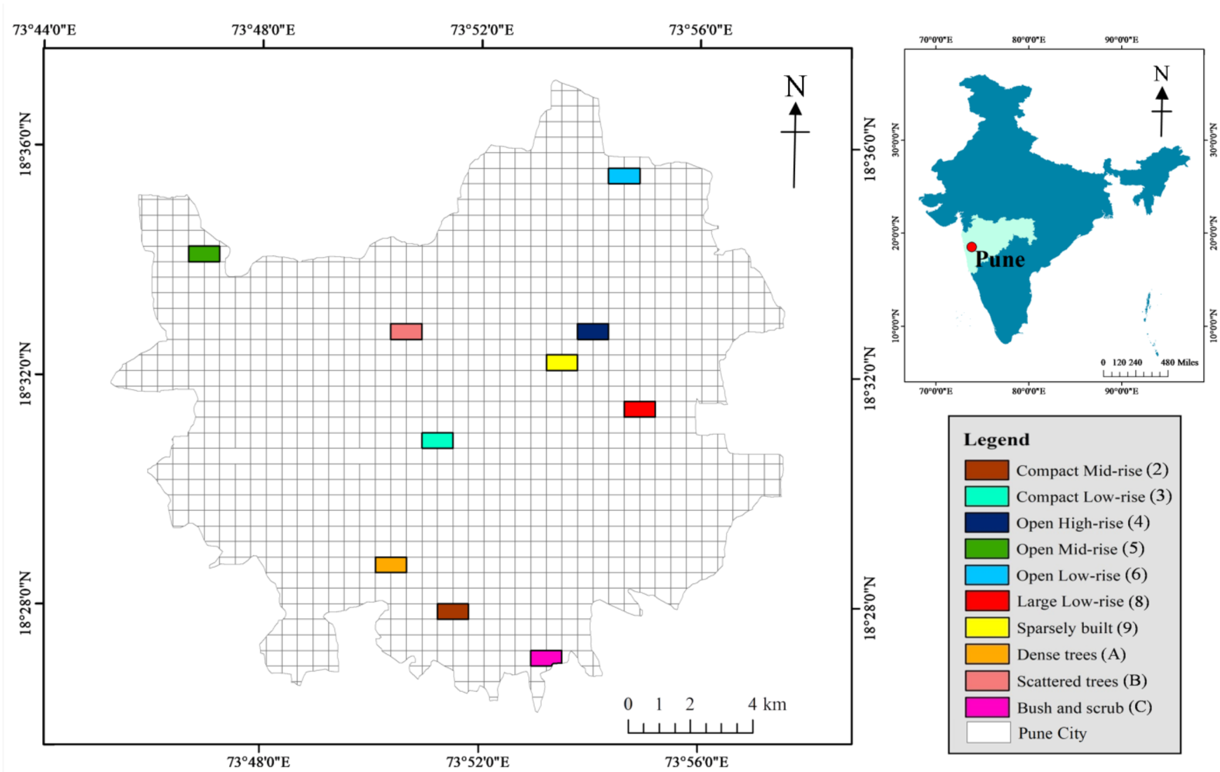

Figure 1. Selected sites for LCZ in Pune city

Table 1. Selected LCZs and their description

LCZ	Tone	Type	Description
2		Compact mid-rise	Dense mix of mid-rise buildings (3-9 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.
3		Compact low-rise	Dense mix of low-rise buildings (1-3 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.
4		Open high-rise	Open arrangement of tall buildings to tens of stories. Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.
5		Open mid-rise	Open arrangement of mid-rise buildings (3-9 stories). Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.
6		Open low-rise	Open arrangement of low-rise buildings (1-3 stories). Abundance of pervious land cover (low plants, scattered trees). Wood, brick, stone, tile, and concrete construction materials.
8		Large low-rise	Open arrangement of large low-rise buildings (1-3 stories). Few or no trees. Land cover mostly paved. Steel, concrete, metal, and stone construction materials.
9		Sparsely built	Sparse arrangement of small or medium-sized buildings in a natural setting. Abundance of pervious land cover (low plants, scattered trees).
A		Dense trees	Heavily wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
B		Scattered trees	Lightly wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
C		Bush, scrub	Open arrangement of bushes, shrubs, and short, woody trees. Land cover mostly pervious (bare soil or sand). Zone function is natural scrubland or agriculture.

2.3 Selection of LCZ Training Areas

The selection of locations has been carried out in many steps. For initiation, the most suitable sites for Pune city within the given LCZ scheme by Stewart and Oke (2012) were identified. For site delineation a fishnet of 500m resolution was produced within the boundary of Pune city which was superimposed as a layer in Google Earth and sites were demarcated. Each LCZ of 500m X 1000m was then clipped and saved as a bitmap image for further use in ENVI-met as the base map.

2.4 Configuration set up for Simulation

For every LCZ a 60X30X30 area was set in ENVI-met with 2m resolution in each direction. The soil type of Pune City doesn't match with the soil types available in the software. Moreover, there is no provision for creating soil. Therefore, the default soil type was selected.

As April is the hottest month of Pune, the daily T_a of the month of April from the year 1969 to 2015 has been averaged to derive the warmest date. The result reveals that 20th and 21st of April are the hottest two dates amongst whom, 21st April has been chosen for simulation configuration. Temperature and humidity forcing have been used with the help of both primary and secondary data. In this method, simulation is operated on the basis of maximum and minimum value of these two parameters. Also, there is a solar radiation adjustment factor by which we can input the global radiation value of the concerned area.

The most important factor in a simulation configuration is to choose a date, start timing and duration of the simulation. The output interval can be set ranging from 10 minutes to 1 hour based on requirement of study. This current study uses two different types of simulations one with 15 minutes and another with 1 hour interval.

3. SIMULATION OF SELECTED LCZS IN ENVI-MET

Urbanization results in an increased proportion of radiative surfaces. Thus, compactness and height of the settlement play a crucial role in decreasing the long-wave radiation losses. This will eventually result in the night time elevated T_a condition within the city. The increased amount of paved surface will also let a minimal amount of heat to be stored as latent heat. Thus, sensible heat will increase. Due to this alteration of natural surface energy and radiation balance, the urban areas happen to be a distinct warm place (Stewart and Oke, 2012). Along with these, decrease in evaporative surface will lead to lowering of specific humidity which in turn will put impact upon the RH. Now-a-days, WS is also severely studied as it is influenced by the urban canyon geometry (Oke, 1988). To study the variation of these atmospheric parameters with respect to changing urban morphology, the site metadata has been provided by Stewart and Oke in their paper of Local Climate Zones in 2012.

3.1 Air Temperature

Simulation has been run for 12 hours to analyze the variability of T_a. Maximum T_a with respect to LCZ (Table 1) at any point of time is far more stable than minimum T_a (Figure 2). Thus, we can say that the minimum T_a is under the effect of type of LCZ and the range of T_a is strongly negatively correlated (~0.99) with the minimum T_a of LCZs i.e., with the elevation of minimum T_a the range of T_a decreases.

For LCZ 4 (open high rise) variation of minimum T_a from morning to afternoon is very high while for LCZ 2 (compact mid-rise), 3 (compact low-rise), 5 (open mid-rise) and 6 (open low-rise) the same is very low and for the rests it is average (Figure 2). On average, morning (9:00 am) is colder than evening (7:00 pm) (Figure 3a). The inter-LCZ range of T_a is mostly variable during the noon hours (Figure 3b). At 3:00 pm for LCZ 4, A (dense trees) and C (barren land) it is very low while for LCZ 2, 3, 5, 6 and B (scattered trees) it is greater than 14˚C. This is mainly attributed to the compactness of the site and building materials. For different LCZs different building materials have been used accordingly. Amongst them there are five types of building materials found in the study which are concrete slab (hollow block), burned brick, concrete light weight and steel one layers from the simulated results we can find different reactions of different materials at the same time of the day (Figure 4). It is negligible during the morning (9 am) but this difference is huge during the noon (3:00 pm) and evening (7:00 pm) hours. In noon hours where the maximum temperature of burned bricks and concrete blocks reach 24℃, the same of single layer steel buildings starts from 24℃ at very small parts and for most of the parts it reaches 28℃. The minimum temperature in some very minute patches is slightly low during noon hours which bring the average temperature of that time down. But in major parts the temperature gets already elevated within the noon hour. Burned brick buildings are the worst reactant to the same.

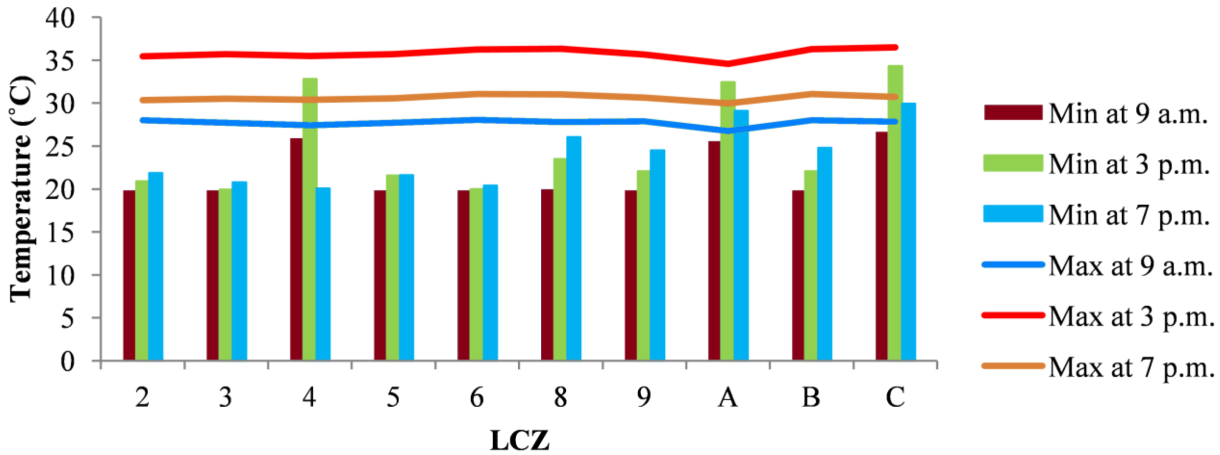

Figure 2. T_a condition at different times at different LCZs showing that the maximum T_a is stable while the minimum T_a varies throughout the day over various LCZs (LCZ 2 Compact midrise, LCZ 3 Compact low-rise, LCZ 4 Open high-rise, LCZ 5 Open mid-rise, LCZ 6 Open low-rise, LCZ 8 Large low-rise, LCZ 9 Sparsely built, LCZ A Dense trees, LCZ B Scattered trees, LCZ C Bush, scrub)

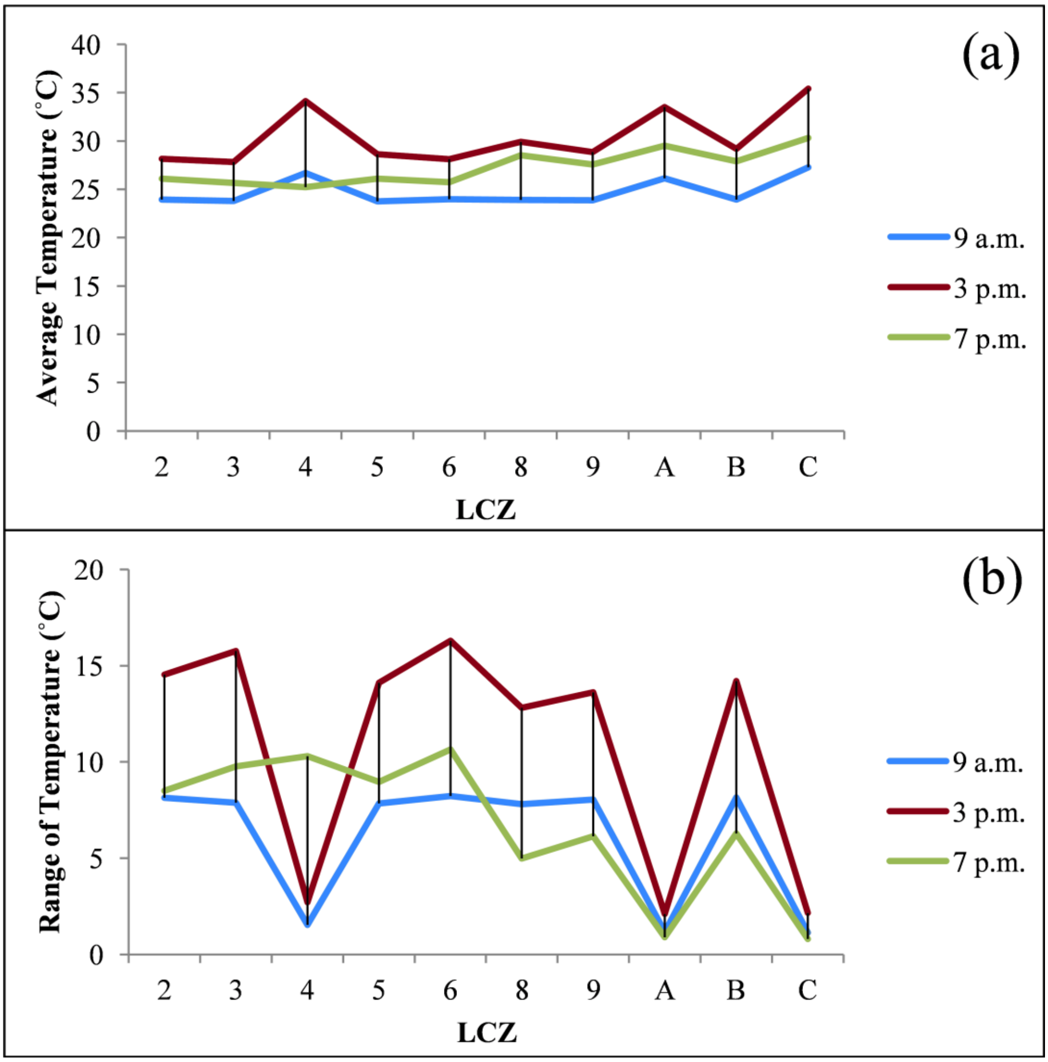

Figure 3. Trend of (a) Average T_a and (b) range of T_a

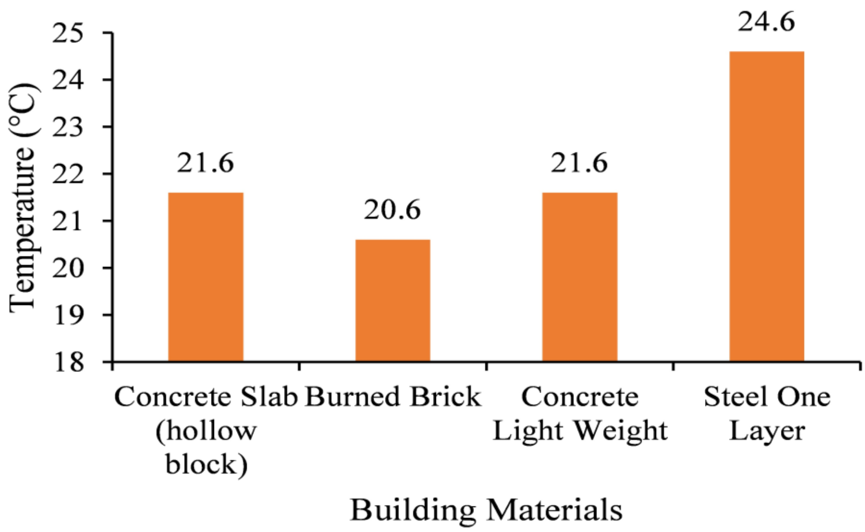

Figure 4. Temperature condition of different building materials at 3.00 pm shows that the metal roof holds the highest surface temperature over the other materials

The UHI effect usually reaches its maxima at 9:00 pm (Weng and Yang, 2004) but sometimes the barren open grounds, be at the outskirts or within the city, happen to be the warmest area compared to the city core which is termed as heat sink (Weng and Yang, 2004; Shah and Ghauri, 2015). For small temporal scale studies, heat sinks are more commonly found during the afternoon hours. LCZ C which is taken as the barren land in the present study is the warmest amongst all within the simulation period with average T_a of 27.26 °C at 9 a.m., 35.41°C at 12 noon and 30.33°C at 7 pm. During the afternoon hours it can be attributed to the heat sink effect. In the morning hour as well, LCZ C on an average is showing up to be warmest despite the fact that there are small warm patches, slightly warmer than LCZ C, forming in LCZ 2 which is a compact mid-rise area (Figure 5). It is mainly due to the shading produced by the surrounding building geometry that some narrow gaps within the buildings are portraying a cooler temperature throughout the day than its surrounding open areas which in turn bring down the average T_a of LCZ 2 lower than the homogeneous LCZ C.

3.2 Relative Humidity

The RH is a highly dependent variable upon T_a but there are many other factors such as wind which modifies the same. It is the ratio of the amount of water vapor present in the given atmosphere to the maximum amount of water vapor that the given atmosphere can hold. The average RH of 9:00 am (42-48%) is far more elevated than that of 7:00 pm (34-44%) (Figure 6). The average RH at 9 a.m. is also far less variable than that at 3:00 pm and 7 pm across different LCZs (Figure 6). Average RH of 3:00 pm is showing the most irregularity with respect to LCZ 2 to 9 and A to C different LCZs.

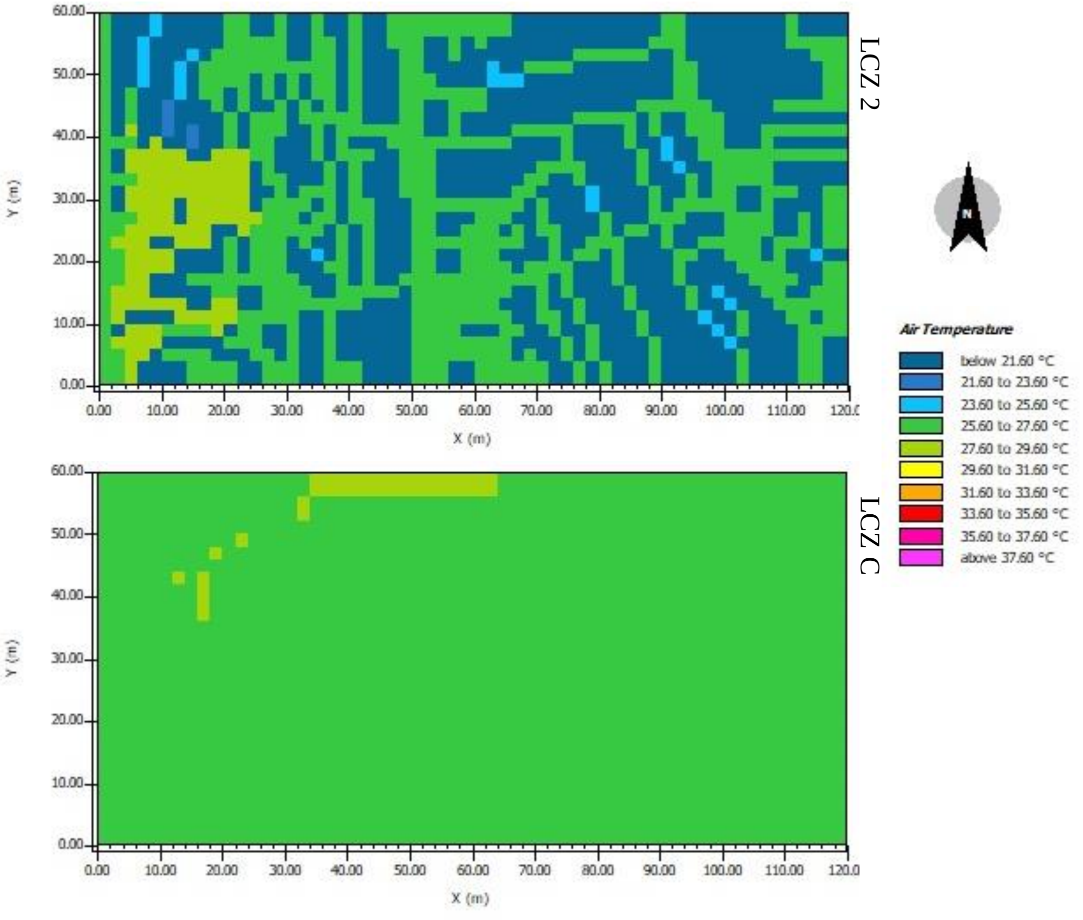

Figure 5. T_a simulation output map of 9.00 am shows the formation of small warm patches in LCZ2 which a slightly warmer than the homogeneous LCZ C

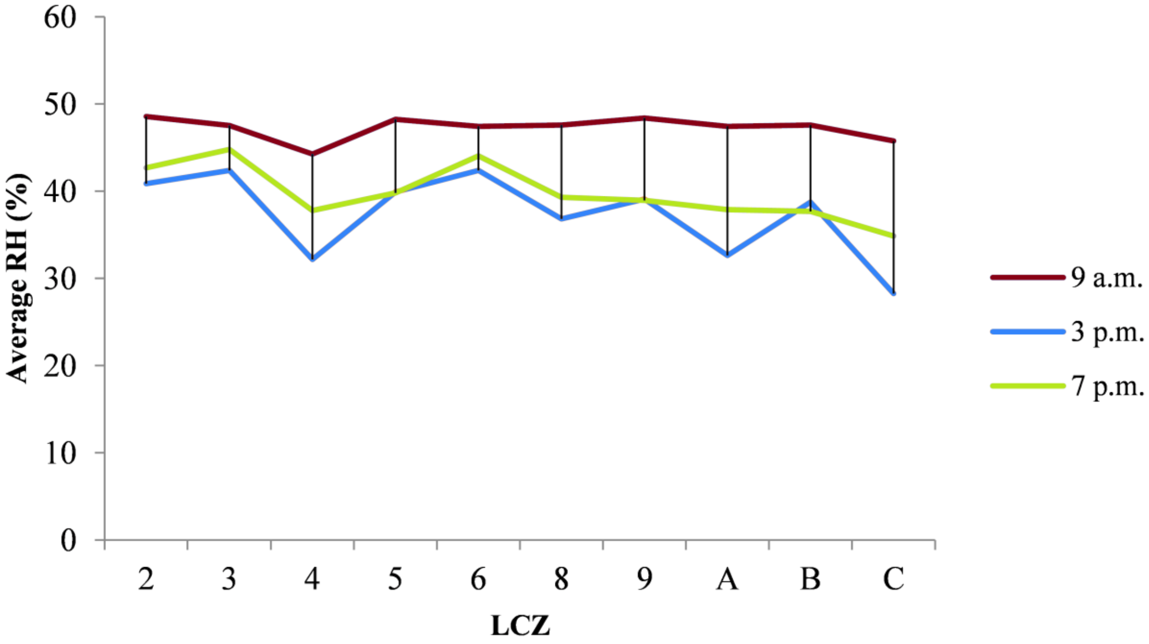

Figure 6. Condition of average relative humidity over LCZs at different times

LCZ A is a region with only dense vegetation cover which can normally be expected to present a highly humid condition with higher percentage of RH (or at least higher than the densely built-up area). In Figure 6 we can see that the average RH of LCZ A is always slightly lower than LCZ 2 which is a compact built-up area. Sometimes built-up areas show higher amounts of absolute humidity than adjacent partly (65%) shaded parks due to irrigation in private gardens (Potchter *et al.*, 2006) inside the built-up area. In the present study, such inputs were not there which implies that the reason lies elsewhere. First of all, as the average T_a of LCZ 2 has been brought down by its colder building blocks, thus, average RH is normally slightly higher than LCZ A. Secondly from the maps (Figure 7), some building blocks have been found which are cold and showing a high RH value. There are only very few studies (Ambrosini *et al.*, 2014; Wang *et al.*, 2019) available that contain supplementary figures of the output map of RH. In one of them (Ambrosini *et al.*, 2014), all the building blocks are pink which denotes RH value >46% but only the RH value of the open spaces were considered for the study. In the present study this is not only found in LCZ 2 but also in some other built-up areas as well (LCZ 3, 5, 6, 8, 9, B). These blocks are very isolated and situated only along the southern, eastern and northern boundary. This isolated high value of RH is pulling up the average RH of LCZ 2 higher than in LCZ A where there is no built-up at all. From particle flow analysis we can see that the regions where particles are higher, in turn, which means that the wind flow is greater, RH value has gone down in those areas. This kind of phenomena is normally found in shallow street canyons whereas in deep canyons wind speed goes considerably down, resulting in a comparatively higher and stable RH (Johansson, 2006). These isolated highly humid building blocks are deficient of wind flow for their location. Such obstacles are not present in LCZ A which is bringing down the average RH lower despite the fact that this is the most vegetated area amongst all LCZs. These building blocks are in the same range (according to the legend) throughout the day except the exact value has gone down from morning to evening. But if only the open spaces in the built-up area are considered, then LCZ 2 shows lower range of RH than LCZ A.

3.3 Mean Radiant Temperature

T_{mrt} is mainly useful in calculating Physiological Equivalent Temperature (PET). From Figure 8, we can see that almost all the LCZs maintain their trend throughout the day. Variation in T_{mrt} in different LCZs is almost the same for all the LCZs. Even, both the maximum and minimum T_{mrt} during morning and afternoon are very much stable with respect to different LCZs. The range of maximum and minimum T_{mrt} happens to be very small in the evening hour, but from morning to noon it is slightly higher. T_{mrt} of evening 7 shows to be lower than the morning 9. It is also greater over LCZ C than LCZ 2. Radiative heating of objects depends on several criteria, one of which is the difference of temperature between objects which also implies that the difference in the surface temperature of the building facades will have an impact on T_{mrt}. But the version of the software that is used in the study does not simulate the T_{mrt} for building blocks which makes it impossible to infer its impact on the same. It simulates the T_{mrt} condition of the open spaces only. SVF, as is defined as the ratio between the radiation received (or emitted) by a planar surface and the radiation emitted (or received) by the entire hemispheric environment (Li *et al*., 2019), is a widely used parameter to estimate the radiative thermal condition of the outdoor spaces. Studies (Wang and Akbari, 2014; Kruger *et al*., 2011) have found that there is a direct and strong correlation between SVF and T_{mrt}. SVF, which is also defined as the ratio between visible sky area of a point in space to the total sky area (Miao *et al*., 2019), brings aspect ratio in the picture. Aspect ratio is defined as a ratio of building height to width of street canyon. So, when the height of buildings increases or the gap between them reduces, the aspect ratio increases while the visibility of sky i.e., the SVF gets reduced (Miao *et al*., 2019). Here comes the efficiency of buildings in shading the streets that urban canyons with higher aspect ratio (>2) get more benefit of shading from surrounding built geometry (Ali-Toudart and Mayer, 2006). So, it is a known fact that if the building blocks produce shades by obstructing the direct solar radiation, then the day time T_{mrt} can be lowered (Lai *et al*., 2019). Thus, we can infer from the simulation output that the present building configuration of the LCZ 2 (aspect ratio >2 (Stewart and Oke, 2012)) is successfully creating a scenario that is indeed helping to keep its T_{mrt} lower than LCZ C (0.25-1 (Stewart and Oke, 2012)). Along with this, ENVI-met simulation program has issues like over estimation of T_{mrt} (Acero and Arrizabalaga, 2018).

3.4 Wind Speed

The initial WS (2.0 m/s) and WD (west=270˚) has been kept the same for all the LCZs. No major temporal changes or differences with respect to different LCZs have been found. For compact built-up areas it shows that wind from the westward direction is unable to penetrate into the built-up area (Figure 9). It is restricted by the compactness not by the building height which is why both in compact mid-rise (LCZ 2) and low-rise (LCZ 3) the conditions are the same. The restricted wind swirls at the western part and forms circles of slightly higher WS.

But the situation is slightly different in the open (Figure 9) or sparsely built-up spaces (Figure 9). Here the wind from the west can easily invade the settlement area. Thus, the concentration of elevated WS in a particular place has not happened. Otherwise LCZs with lesser roughness (A and C) get almost an equal distribution of WS everywhere.

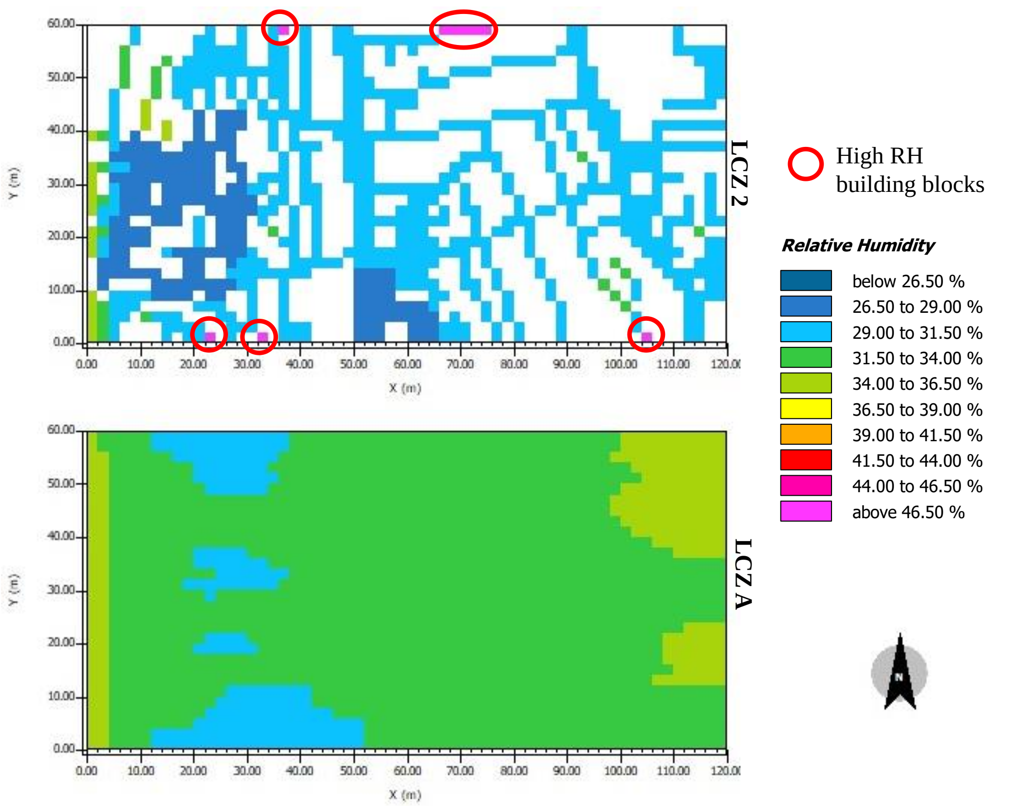

Figure 7. RH simulation output map of 3.00 pm is pointing out some building blocks with high RH value

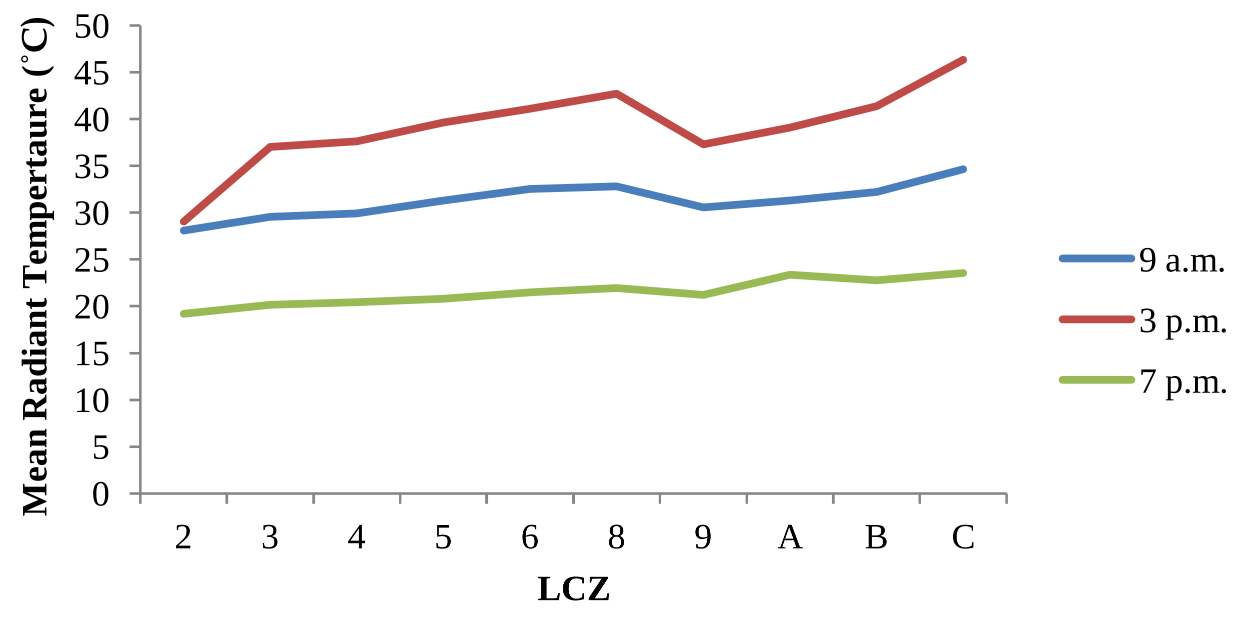

Figure 8. Simulation output of average T_{mrt} over LCZs at different time shows that throughout the study period T_{mrt} is higher over barren lands than built-up areas

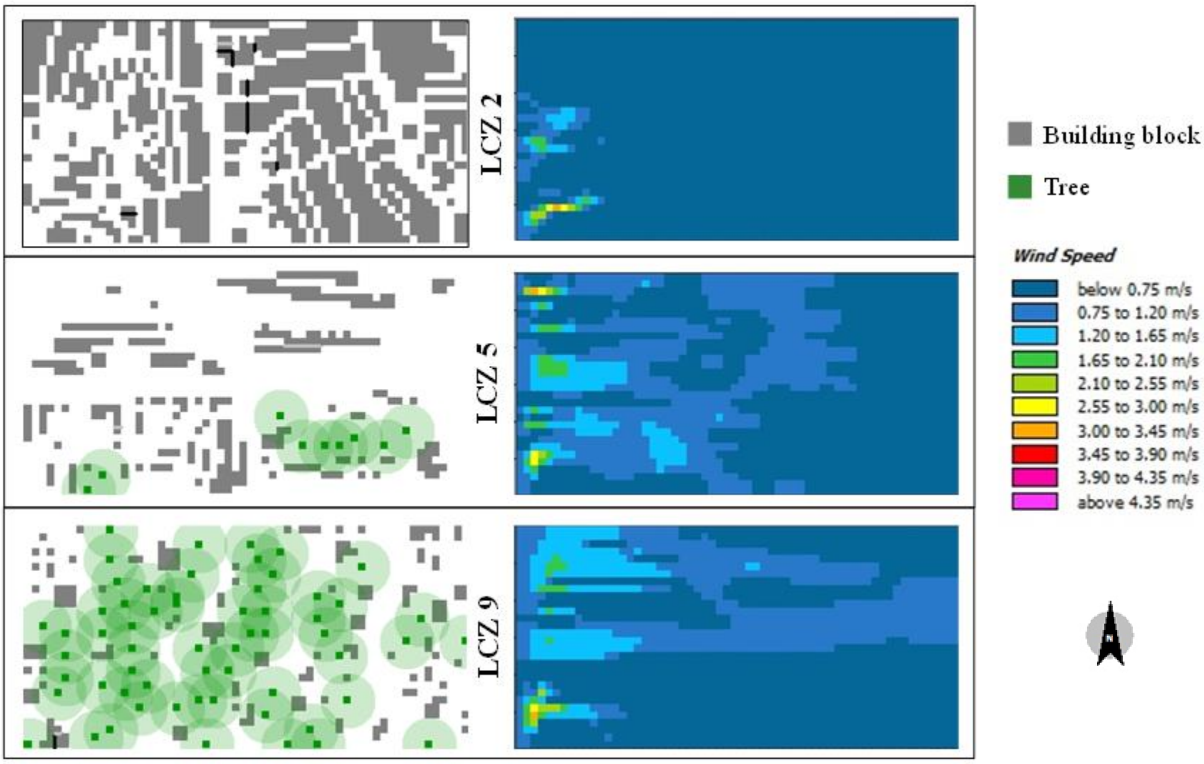

Figure 9. Distribution of wind speed at 3.00 pm in three different (LCZ 2, 5 and 9) building scenario shows that with lesser compactness of the settlement, ventilation of wind is increased

4. RESULTS AND DISCUSSION

To verify the attenuation of the selected meteorological parameters with reference to urban morphology, represented by LCZ classification, the simulation was performed in of ENVI-met software. The ground checking was carried out for confirming if prescribed LCZ types (Stewart and Oke, 2012) are in accordance with the actual urban fabric and particularly morphological features at the selected sites. ENVI-met software has been thoroughly tested by several researchers (Acero and Arrizabalaga, 2018; Ozkeresteci *et al*., 2003; Chow *et al*., 2011). ENVI-met simulations are established to provide strong correlation with the observed values in terms of T_a and RH (>0.9) (Acero and Arrizabalaga, 2018). For T_a it is the most reliable. However for T_{mrt} ENVI-met simulation results are not well correlated due to a variety of factors discussed in detail by several studies (Acero and Arrizabalaga, 2018; Gál and Kantor, 2021). In the case of cloudy days, morning and afternoon hours, simulations overestimate the T_{mrt} while for the noon hours or sunny day it is more accurate (Acero and Arrizabalaga, 2018). This can be attributed to the nature of the globe thermometer. The standard diameter given for the globe by ISO is 0.15m with a standard emissivity of 0.95. Smaller the globe diameter more is the inaccuracy in T_{mrt} reading. Amongst all the chosen parameters, a correlation between simulated and ground value of WS is found to be the lowest (Acero and Arrizabalaga, 2018). The reason is that the model provides the simulation results singularly based on WS and WD input which eventually doesn't change throughout the simulation period. Thus, both over and under estimation of WS data have occurred (Acero and Arrizabalaga, 2018).

The comparison of the output for local climate zones titled as LCZ 2, LCZ 3 and LCZ 5 was accomplished. Among these LCZs compact sites are represented by LCZ 2 and LCZ 3, while LCZ 5 is an open site (Table 1). The further specifications for above discussed LCZs are, LCZ 2 and 5 contained mid-rise buildings while LCZ 3 contained low-rise buildings (Table 1). Both the differential height and compactness of buildings play a significant role in cooling or heating of building canyons by modifying the wind flow and penetration of the insolation (Kariminia *et al*., 2015). Thus, in the present study these two factors were kept as primary criteria and the aim behind such selection was to compare and understand the situation in different combinations of scenarios. Along with these, the locations of the LCZs were chosen in such a way that they spread all over the city homogeneously. Hence, LCZ 2, 3 and 5 were selected. Two different time spans selected for the comparison are noon hours (1:00-3:00 pm) and afternoon hours (5:00-7:00 pm). In the afternoon hours temperature decreases more quickly from 5:00 pm to 7:00 pm compared to the rate of increases in the noon hours from 1:00 pm to 3:00 pm. In the afternoon hours the range of temperature is meager in the LCZ 2 which is a compact built-up area while it is greater in LCZ 5 which happens to be an open built-up area. It may be due to building shadow effect in compact mid-rise (LCZ 2), however in LCZ 5 open spaces allows higher penetration of incoming solar radiation. During noon hours range of temperature in LCZ 3 is low but temperature remains high as observed in LCZ 2 as both are compact built-up area. Thus, it may be inferred that T_a simulation has shown an overall good correlation with the field observations for both the compact built-up zones, but simulation results are highly correlated in case of open mid-rise i.e LCZ 5. For LCZ 2 (Figure 10.1.a) and 3 (Figure 10.1.b) the simulation shows a medium correlation with the field observation (~0.5). However, it shows (Figure 10.1.c) a very good correlation (~0.9) with a T_a for an open built-up area i.e., LCZ 5.

Besides T_a, RH simulation depicts distinct characteristics for simulation results. It is observed that, for LCZ 2 and 5 for afternoon hours (5:00 pm to 7:00 pm) the RH increases at a quite good rate though the earlier LCZ represents compact mid-rise scenario and later is open mid-rise. Thus, in the case of RH there is no notable change indicated like what has been observed in T_a. While comparing the simulated data with the field observation we can find a distinct feature in ASE of the RH simulations. For all the different LCZs there is a slight overestimation represented by the model results (Figure 10.2).

After analyzing linear correlation regression between simulated and the observed data it has been found that for LCZ 5 (Figure 10.2.a) observed and simulated RH is strongly correlated (~0.9) which represents open mid-rise, for LCZ 2 (Figure 10.2.b) the correlation is medium (0.55) and for LCZ 3 (Figure 10.2.c) it is very weak (~0.4). From this result it can be observed that the correlation between the simulation and the ground observation of RH is somehow dependent upon the type of LCZ under consideration. In Figure 7, the individual blocks of high RH are observed between the building canyons which may be due to high moisture accumulation in the urban canyon due to inaccessibility of active wind flow.

The simulation results for T_{mrt} have depicted distinct phenomena which have been discussed in detail. The formula used in the present study is given by Thorsson *et al*. (2007) wherein they come up with a new mean convection coefficient which represents better correlation between the outputs from the above mentioned two methods. It was observed that, during noon hours that is 1:00 pm to 3:00 pm the rate of decrease in T_{mrt} is comparatively less than what has been observed for afternoon hours (5:00 pm to 7:00 pm. The correlation results of T_{mrt} with other meteorological parameters confirm that the T_{mrt} has feeble correlation with T_a and globe temperature, while it is better mainly correlated with the WS and the diameter of the globe.

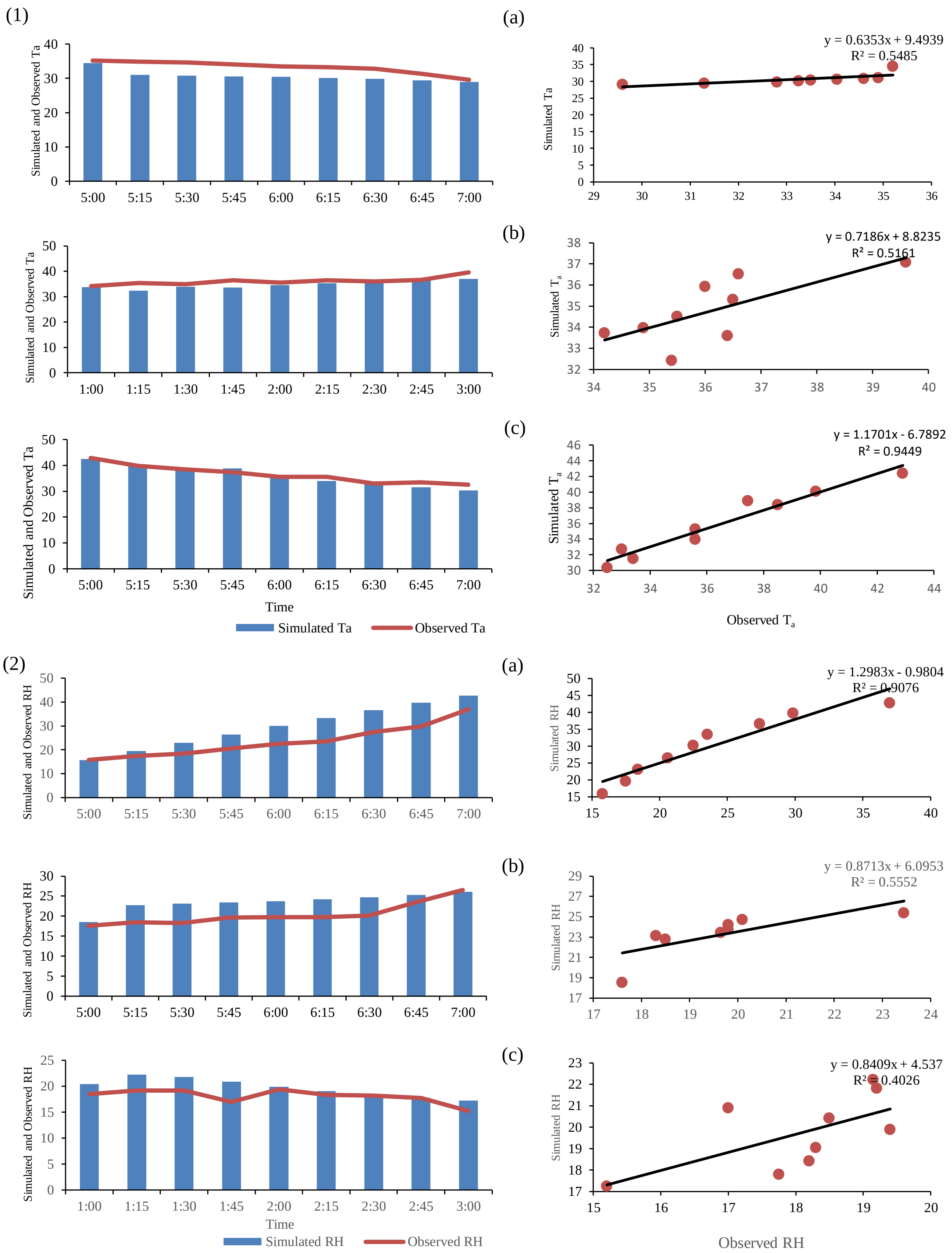

Figure 10. Comparison between simulated and observed (1) T_a, (2) and RH (3) T_{mrt} at a. Balaji Nagar (LCZ 2) b. Mandai (LCZ 3) c. Balewadiphata (LCZ 5) during noon and afternoon shows the complex relation between then with respect to time and compactness of the LCZ

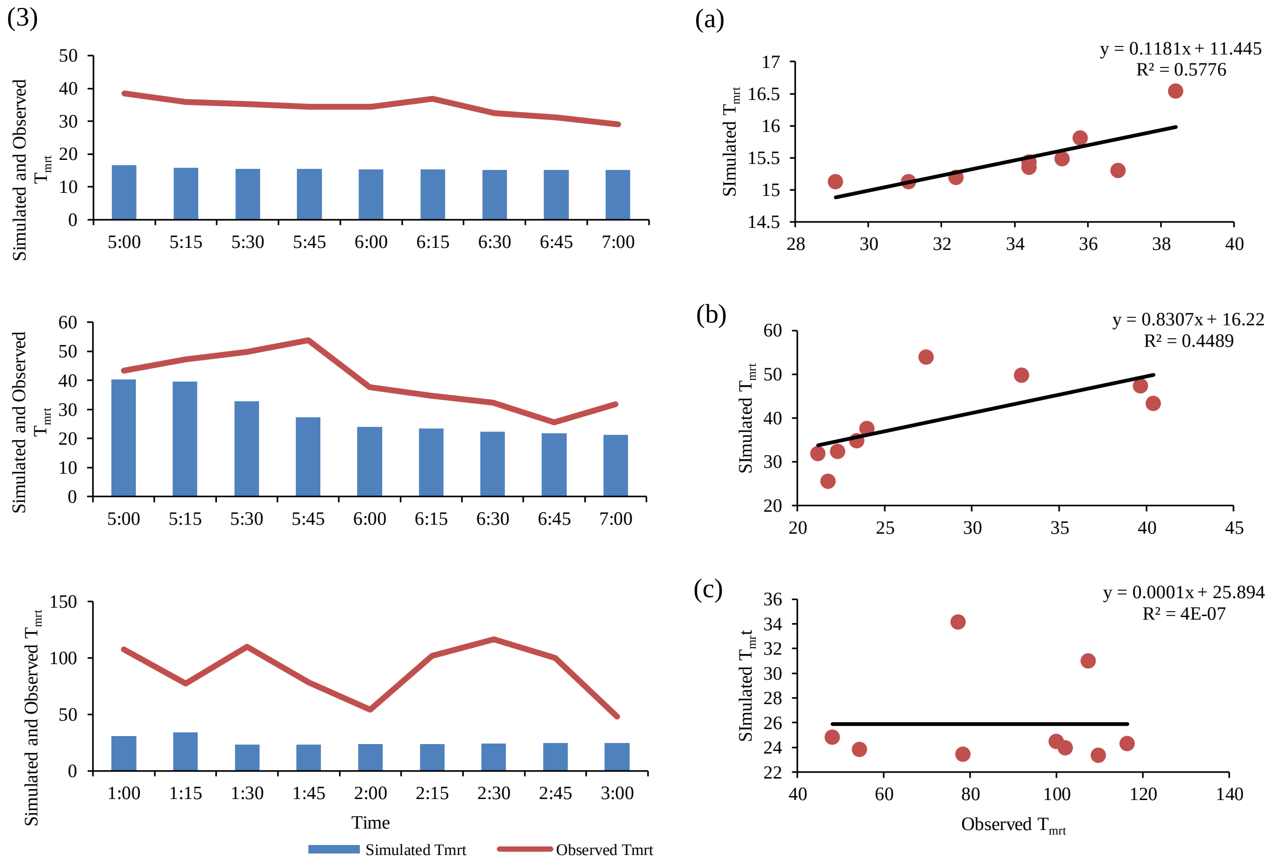

Figure 10. Comparison between simulated and observed (1) T_a (2) RH (3) T_{mrt} at a. Balaji Nagar (LCZ 2) b. Mandai (LCZ 3) c. Balewadiphata (LCZ 5) during noon and afternoon shows the complex relation between then with respect to time and compactness of the LCZ

Earlier research studies have found that ENVI-met is not much accurate in estimating T_{mrt}. Depending upon the solar radiation adjustment factor it tends to overestimate short-wave solar radiation for the whole day which eventually results in an over estimated T_{mrt} during the afternoon hours (Acero and Arrizabalaga, 2018). Compared to that, it gives a more reliable estimation in the noon hours more precisely at 12:00 noon (Acero and Arrizabalaga, 2018). In the present study, a completely distinct condition is observed. First of all, underestimation of T_{mrt} is found for all the LCZs and at both (1:00 to 3:00 pm and 5:00 to 7:00 pm) the time span. It appears to seem that underestimation during afternoon hours is slightly lesser as compared to that in the noon hours. Moderately good correlation between the simulated and the observed T_{mrt} during the afternoon hours at LCZ 2 (Figure 10.3.a) and LCZ 5 (Figure 10.3.b) adds strength to this perception. The T_{mrt} correlation is found very weak during the noon hours (~0.0) at LCZ 3 (Figure 10.3.c). According to studies (Acero and Arrizabalaga, 2018; Gàl and Kantor, 2020) the main problem lies in the model of radiation that is used in ENVI-met to simulate T_{mrt}. While simulating a site on sunny day with a configuration of direct solar radiation at the site, the model assumes the sites to be under shadow (Acero and Arrizabalaga, 2018). This causes a lowered estimation of the shortwave radiation. But, during the ground measurement of the present study, the instrument was kept in direct solar radiation, away from any kind of building or tree shades. Hence, the observed T_{mrt} goes higher than the simulated values of the same during the noon hours which results in a weak correlation between them. Also, one major problem that we faced while using the software was its solar adjustment factor. The solar adjustment factor configuration window keeps scaling the radiation values down whenever the default value was updated with some other value. There is no option of changing the initial shortwave and long wave (or any other radiation parameters) in the model. All the values change proportionately in a predefined ratio with the changing solar adjustment factor. Therefore the ENVI-met model is not able to choose appropriate inputs for T_{mrt}. Gàl and Kantor (2020) have faced the same issue during their study. They also found that the software lags in estimating the surface temperature of different materials (both building and natural surfaces) which is also a possible attribute to the errors. The model seems to have better performance in temperate latitudes where radiation input is less, however the accuracy of the model gets affected for tropical high radiation regions (Lindberg *et al*. 2013).

The simulation results for WS have not provided accurate results. As the WD and wind velocity in the model need to be predetermined, the fluctuation in wind flow in accordance with the complex urban geometry is not better reflected through ENVI-met simulations. The eddies and turbulence created at the urban boundary layer due to differential building height is a prominent feature of urban wind attenuation, however these local eddies and turbulence caused in a wind direction as well as velocity has not been better captured in ENVI-met simulations (Acero and Arrizabalaga 2018; Lopez-Cabeza *et al*. 2018; Li *et al*. 2019). Although WS indirectly affects the T_{mrt} by carrying the heat from one place to other through convection and eventually reduces the heat component. In case of simulation and observation comparison, from the comparison table (Table 2) itself it is visible that ENVI-met does not consider the change in WS. None of the changes in WS during observation is simulated be it whatever the time of the day.

Later to the simulation of selected meteorological parameters the study comes up with the findings that on the warmest date of the year for Pune city, morning is quite colder than evening. Different elements of LCZs greatly modify the minimum T_a. Building material is one very important element amongst them. Although it hasn't shown much impact upon the T_a of its adjacent atmosphere, it has significantly changed the average T_a.In case of T_a simulations, heat sinks have formed at the micro-scale barren lands which makes them warmer than the city core. RH, being mainly dependent upon T_a, has shown a very strong inverse correlation with it both spatially and temporally. Other than this, wind flow as well has shown its impact on modifying the RH. Relation of simulation and observed T_a and RH can be attributed to the compactness of the site as, for open sites (LCZ 5) the correlation value is very high but for compact sites (LCZ 2 and 3) it is only moderate which in turn means that ENVI-met simulates these two variables better for openly built-up zones. In the case of simulation of T_{mrt} it shows far more stability with respect to the changing LCZ, but for the relation between simulation results and observed T_{mrt} the estimation becomes inaccurate as the model either underestimates or tends to overestimate T_{mrt}. With the model mechanism it was expected that it will slightly overestimate the T_{mrt} during the afternoon hours and will be near to accurate for the noon hours. The simulation shows something completely contradictory to it. The relation with the other climatic factors used in the formula for calculating the T_{mrt} are also very weak. The formula used in the present study for calculation of T_{mrt} requires T_a, globe temperature, WS and diameter of the globe thermometer. Smaller the globe diameter increased is the inaccuracy in measurement of globe temperature. The standard diameter given by the ISO is 0.15 m while the diameter of the Kestrel Heat Stress Tracker is only 0.0254 m. The inaccuracy in calculating T_{mrt} from the observed data can be attributed to this. The relation of WS and urban morphology is affected by the compactness. WS is showing spatial variability with respect to compactness of the built-up. It is highly restricted by the compactness of the built-up area as it constraints the wind flow, that is, the more compact the urban forms, less is the penetration of wind inside the area. In the case of relation between the simulation and observation of WS from the comparative data table itself it is clear that the simulation model doesn't at all simulate the temporal variability of WS. It is mainly done on the basis of initial WS given as an input parameter. Overall the simulation by ENVI-met for T_a and RH shows a good relation with the field observation while the same for T_{mrt} and WS is showing a very feeble correlation.

Table 2. Comparative simulated and observed data for Wind Speed

BALAJI NAGAR LCZ 2			BALEWADIPHATA LCZ 5			MANDAI LCZ 3		
Time	Initial WS (m/s) = 0.1		Time	Initial WS (m/s) = 0.2		Time	Initial WS (m/s) = 0.9	
	Simulation	Ground		Simulation	Ground		Simulation	Ground
5:00	0	0	5:00	0.32	0	1:00	0.01	1.7
5:15	0	0	5:15	0.32	0.3	1:15	0.01	0.6
5:30	0	0	5:30	0.32	0.5	1:30	0.01	1.5
5:45	0	0	5:45	0.32	0.3	1:45	0.01	0
6:00	0	0	6:00	0.31	0	2:00	0.01	0.7
6:15	0	0.2	6:15	0.31	0	2:15	0.01	1.15
6:30	0	0	6:30	0.31	0	2:30	0.01	1.6
6:45	0	0	6:45	0.3	0.8	2:45	0.01	1.5
7:00	0	0	7:00	0.3	0	3:00	0.04	0

5. CONCLUSION

The ENVI-met simulation results and ground checking for the selected land parcels are discussed in detail. The ENVI-met simulations for the meteorological parameters selected differ according to varied urban geometry, urban morphology as well as depending on urban materials. The detailed investigations for different urban configurations represented by LCZ scenarios have reached the following inferences. There are distinct microclimatic differences with changing urban morphology as represented by LCZs with respect to weather parameters considered; T_a, RH, T_{mrt} and WS. ENVI-met simulations for T_a and RH have provided excellent results compared to the other two parameters. However, for WS and T_{mrt}, as many studies have already suggested (Acero and Herranz-Pascual, 2015; Acero and Arrizabalaga, 2018; Gál and Kántor, 2020), the model results are still an underperformer, specifically for a city with a tropical semi-arid climate. There is a possibility that built-up areas have led to increased radiative surfaces. This may have ultimately reflected in the development of urban heat sinks. It is also impacting RH due to the increase in impervious surfaces. In LCZs representing barren areas and compact built-up areas, the obvious effect of high T_{mrt} has been observed with increased values of T_a and RH. Simulation has distinctly shown a conspicuous scenario with greater T_a over the barren lands than the city core. These barren islands within the city limits act as a heat sink and thus requires thoughtful planning to replace underutilized heat sinks into green areas which can be efficiently used for recreational purposes. ENVI-met 4.3 output results for T_{mrt} do not simulate the radiative properties of building blocks. If building facades T_{mrt} could be checked then it will result in higher T_{mrt} than the open spaces or barren lands with better ENVI-met version availability. However, the model fails to consider reflected and re-refracted long wave radiation within the compact building structures that may have resulted in lower T_{mrt} within built-up city canyons than a barren land. It is a well understood fact that the differential height of buildings leads to formation of shaded areas in the city core, which also reduces daytime T_{mrt} in the city core by blocking the direct solar radiation. This has also led to comparatively lesser temperature during afternoon hours (Lai *et al*., 2017). The simulation result of the present study confirms the effect of shading in lowering T_a, as it already shows a greater temperature over the barren lands than city core due to heat sink effect. However, the simulation output depicts that the kind of shading produced by the compactness of LCZ 2 and 3 that has indeed proved helpful in reducing radiative sensible heat in the city core. The simulation output for WS found that increasing compactness readily restricts the penetration of wind flow inside the settlement. It is known that the cooling effect of the flowing wind has a significant impact upon reducing the intensity and hostile effects of UHI (Rajagopalan *et al*., 2014). Even when air flow in the street canyons is restricted by street trees close to the buildings and thus reduces the WS, it causes significant rise in both T_a and T_{mrt} (Li *et al*., 2019). Combining different street orientations and aspect ratios Kariminia *et al*. (2015) found out that though the orientation of the street with respect to solar radiation is important for the thermal condition for the canyons but aspect ratio of the street canyon has more control over the day time T_{mrt} i.e., by increasing the aspect ratio from 0.1 to 0.3 the day time T_{mrt} could be significantly decreased. The study also found that even though street canyons with lower aspect ratio (0.1) will be irradiated throughout the day resulting in an elevated T_{mrt}, if the prevailing wind direction is parallel to the street and there is proper ventilation for wind flow, small patches of low T_{mrt} can be formed at the spots of high WS. However, though ENVI-met simulation has shown less accuracy in simulating WS, but, in the present study, the city compactness pertaining to its complex geometry eventually results in lowering WS in most of its parts. The further expansion of built-up areas of the city may create a critical challenge for the urban planners to resolve the issue of urban compactness due to haphazard urban sprawl, though compactness allows proper shading effect and counter the potential increase in radiative temperature of city's open spaces and yet ventilation created by movement of air allows to remove excess heat trapped in city canyons and thus enough wind flow becomes necessity particularly for a warm tropical city like Pune. The urban materials eventually contribute to the increasing UHI effect. Considering the findings that building material plays a crucial role in determining the average T_a. The concrete material, burned bricks constructions and use of metal roofs increase the emissivity factor and reduce the albedo in urban areas (Akbari *et al*., 2001; Prado and Ferreira, 2005). Thus, the present study highlights the need for alternative building materials that help in reducing the average T_a at micro-scale. This will in turn help in reducing the long-wave T_{mrt} and emissivity component. The present study though has a major shortcoming of considering discrete LCZs within a study area and fails to consider complete urban fabric, it highlights the contribution of individual urban morphology in attenuating meteorological parameters. The study provides an opportunity to urban planners for micro level study before designing discrete land parcels within a city. To sum up, considering the ongoing research for the calculation of T_{mrt} in ENVI-met software, the present study stresses more efficient understanding of radiative components in the complex urban pattern. The cities undoubtedly create the distinct and complex morphology that is apparent to modify behavior of meteorological parameters with an overwhelming rate of urbanization. However, the better technological input through enhanced simulation urban models may prove helpful to mitigate adverse impact of urbanization for better livelihood solutions.

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ABBREVIATIONS

GIS: Geographical Information System; **IMD**: India Meteorological Department; **LCZ**: Local Climate Zones; **LULC**: Land Use Land Cover; **NDC**: National Data Center; **PET**: Physiological Equivalent Temperature; **RH**: Relative Humidity; **SVF**: Sky View Factor; $\mathbf{T_a}$: Air Temperature; $\mathbf{T_{mrt}}$: Mean Radiant Temperature; **UHI**: Urban Heat Island; **WD**: Wind Direction; **WS**: Wind Speed; **WUDAPT**: World Urban Database and Access Portal Tools.

CONFLICT OF INTEREST

The authors of the paper declare that there is no conflict of interest.

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