Analysis of microclimatic diversity and outdoor thermal comfort perceptions in the tropical megacity Dhaka, Bangladesh

Tania Sharmin[a,1], Koen Steemers[a], Andreas Matzarakis[b]

[a] *University of Cambridge, Department of Architecture, Cambridge, UK*

[b] *Research Centre Human Biometeorology, German Weather Service, Freiburg*

ABSTRACT

The study has observed microclimatic conditions in residential, commercial and educational areas in Dhaka city. Comfort surveys were carried out along with microclimatic measurements. Findings suggest, urban forms that are more variable with irregular plot sizes and building heights, mostly in traditional areas, have positive responses with respect to the synoptic climate, while planned areas with uniform plot sizes and height, shows a tendency to develop daytime urban heat island effect. An east-west orientated street in a formal residential area was found to be 1^{0}C to 3.8^{0}C warmer than a street in a traditional residential area in the same orientation. It is apparent that the differences are directly linked to the specific geometric pattern of the areas and can be defined by the parameters like uniformity versus diversity and compactness versus openness. Uniform heights, equal building separation and plot sizes can lead to harsher urban microclimate, while variety in these may foster positive changes. Lack of such variety can even affect compact urban areas. This is also evident from the analysis of pedestrian's responses in the case-study areas. Pedestrians in the formal planned areas or less diverse traditional areas were found to be less comfortable than those in the more variable areas. A statistical analysis of climatic variables and thermal sensation showed moderately strong and significant correlations. These reveal that urban geometry and the resultant climatic variables may not be the only, but one of the most important factors for governing the outdoor thermal comfort sensation in a tropical climate.

Keywords: Urban microclimate, urban geometry, outdoor thermal comfort, tropical hot-humid climate

[1] Corresponding author, Address: Department of Architecture, 1-5 Scroope Terrace, Cambridge, CB2 1PX, Tel: 01223 332950, *Email: ts531@cam.ac.uk*

1. INTRODUCTION

The focus of this study is primarily on investigating the impact of urban microclimate on outdoor thermal comfort conditions in the tropical megacity of Dhaka. The implications for indoor comfort of the prevalent free-running buildings provide further incentive to improve the city's microclimate conditions. Passive strategies through architectural design are not sufficient to ensure comfortable indoor conditions as far as the hot-humid climate is concerned, especially in the context of high density urban areas [1]. Airconditioning, on the other hand, is beyond the reach of the vast majority of people. Therefore, this paper explores more cost-effective ways to reduce the thermal stress by ameliorating the urban microclimate through urban planning and design.

The urban microclimate is determined by the configuration of the streets, building heights, density and separation of buildings, roughness length, urban permeability, surface materials and their albedo, the presence of vegetation, and anthropogenic heat production [2]. Aside from the last three parameters, the rest are essentially the components of urban geometry. Since these components are mainly determined by urban planners, designers and architects, their role could be vital in reducing the thermal stress and its impact on health, wellbeing and productivity in both indoor and outdoor spaces. However, there are immense challenges in achieving these aims in high-density tropical cities in developing countries where the problems are multifaceted [3].

In Dhaka, rapid urbanisation and unplanned growth of the built environment have led to the urban heat island (UHI) effect and an elevated level of air-pollution [4.5]. The city is experiencing an unprecedented growth in urban population over the recent decades [6]. Aside from the pressure to accommodate the growing influx of migrating people; weak planning control and lack of adequate building regulations have further led to poor building standards with reduced thermal and ventilation performances [7].The current building regulations only define minimum standards of space, light and air as limits to maximise the use of available space. A comparative analysis of the urban forms in Asia, US, Europe, Latin America and Australia shows that urban morphologies of the developing world are more compact and dense than their counterparts in either Europe or North

America [8]. Thus, the resultant urban geometry in Dhaka is comparatively different from those found in the Western (usually colder) countries and therefore the strategies applied to improve their urban microclimate are not necessarily suitable for use in Dhaka.

Airconditioning cannot be an effective solution for the urban dwellers struggling with uncomfortable indoor conditions. The reason is that, not only do very few people have access to airconditioning [9], but also the fact that the country is suffering from acute shortage of electricity supply with the lowest per capita electricity generation in the world [10].Therefore, the city cannot afford to provide an uninterrupted power-supply even to its most developed areas. On the other hand, the use of airconditioning can worsen the situation by increasing the amount of anthropogenic heat release. Air-quality in Dhaka is already at risk due to the emissions from vehicles and the brick kilns around the city [11]. In this situation, passive strategies fail to provide unpolluted and comfortable ventilation inside buildings as the immediate outdoor environment of the buildings is incompatible with the IEQ (indoor environmental quality) demand.

Historically, due to its tropical location, the city's outdoor spaces – including large parks and gardens, *chawks* (squares) and narrow, winding streets –had always been the locus of urban life. Air temperature did not generally exceed 35^0C, providing usable outdoor conditions throughout the year except during rainy days. But over the past few decades, as a result of scarcity of land along with rapidly increasing land-prices, the green spaces in the city and even the flood-plains have been occupied by urban dwellings as a result of profit-driven developers. Reduced vegetation and increased air temperature [7] as a repercussion of densification are directly affecting comfort levels in urban outdoor spaces.

Consequently, an effective strategy to improve the overall microclimate of the city for ensuring a healthy living environment both indoors and outdoors can be achieved through proper urban planning and design. Reducing the density of the city might seem to be a long-term plan and depends on the decentralisation of the capital city, which is often difficult in a developing country where capital is the centre of most economic activity. This imposes on urban planners and designers greater challenges and limited opportunities. Therefore, there is a need to explore alternative possibilities to achieve both indoor and outdoor thermal comfort.

This study, particularly dealing with outdoor thermal comfort, recognises that there are opportunities for improving pedestrian comfort and the outdoor urban microclimate, by modifying the urban geometry through policies related to urban planning and building regulations [12]. The paper focuses on a relatively new area of research and proposes uncommon parameters for urban geometry that might be useful to improve the relationship between urban microclimate and outdoor thermal comfort. Evidence suggests that urban geometry plays a more decisive role than building materials and their albedo effect in shaping the microclimate [13]. Yet, there is a lack of information about the correlation between urban geometry, microclimate and outdoor thermal comfort in a tropical hot-humid climate [14]. Although, there is a growing interest in such climates [15], only a few, such as (Ahmed, 2003) [16], focus on high-density megacities in a developing country context. To address the gap in knowledge, this study compares microclimatic conditions in different urban agglomerations (as explained later in this paper under 2.2) in Dhaka and determines how they affect comfort conditions in the street. The key objectives of this study can be summarised as: i) to investigate the variation in microclimatic conditions in different urban configurations; ii) to understand the role of urban geometry in shaping the variation; iii) to examine the impact of the microclimate on pedestrian thermal comfort, and finally; iv) to test new analysis techniques and methods in a tropical high-density context.

2. MATERIAL AND METHODS

2.1 Study Area

Dhaka is the capital of Bangladesh with a population of 14 million people [17]. It is one of the fastest growing mega-cities in the world, receiving over 300,000 to 400,000 new migrants per annum [18, 19] with an urbanization rate over 2.5% [20]. The city is mostly surrounded by wet-lands with the Buriganga River flowing in the south and south-west, the Turag River in the west and the Balu River in the east, while leaving less opportunity to expand in any direction but north. The 400 year history of unplanned urbanization [17] has left the city with an already built-up urban-core with the new development expanding towards the fringe areas and low-lying flood plains.

Dhaka is located at 23.24°N, 90.23°E with an elevation between 2 to 14 m above main sea level (MSL) with an average of 6.5 m (JICA, 1987, cited in [17]). The city is in a tropical Monsoon climate with a distinct warm-humid rainy season, a hot-dry summer and a short cool-dry or winter season. The mean annual temperature is 25.8^{0}C with an annual range between 39.4 to 8.2^{0}C (http://apps1.eere.energy.gov/buildings/energyplus/). The mean annual relative humidity is 75%.

2.2 Selection of case-study areas

Climate-based classification of cities in previous studies [21, 22, 23, 24] is mostly based on the form and function of modern, developed cities which are less suitable for more diverse economic settings [25]. In order to address this limitation, Stewart and Oke [25] suggested a new system of classification, called "local climate zones" (LCZs), that is: "inclusive of all regions, independent of all cultures, and, for heat island assessment, quantifiable according to class properties that are relevant to surface thermal climate at the local scale". The main variables of the LCZ system include sky view factor, aspect ratio, building surface fraction, roughness length, surface cover (pervious or impervious) and anthropogenic heat output. However, the system is essentially generic and unable to address the diversity of every urban and rural site. The disorganised and unplanned nature of Dhaka city makes it complicated to classify urban areas of Dhaka according to the LCZ system. Initially, according to the 1950-60 master plans, Dhaka was divided into different land-use zones which included residential, commercial, industrial, agricultural and administrative activities. Like any other developing country cities these boundaries are not properly defined. Due to a lack of adequate planning rules and control, all zones have developed mostly as mixed-use areas. However, in order to standardise the climatic classification of the city and to make it comparable with other cities in the world, this study has incorporated new subclasses of the LCZ system along with the primary LCZ classes. The sub classification is an accepted practice in the LCZ system [25].

Figure 1 shows the zoning of planned and unplanned residential areas in Dhaka indicating that the city falls predominantly in the unplanned category. The unplanned zones consist of traditional residential areas as well as squatter settlements. Due to the temporary nature of the squatter settlements, their urban geometry is beyond the remit of this study which only considers traditional residential areas.

In a traditional residential area, which has mainly grown out of spontaneous development under loose planning controls, the building form, heights and sizes will vary, as well as their usage. In many cases, the ground floor of buildings in such an area is used for commercial purposes. The street layouts in these areas often create varying patterns with narrow and twisting streetscapes. Green spaces, especially community areas like parks or gardens, are not common.

The other residential type in the city is formal or planned, with buildings of equal height and width, and roads laid out in a grid-iron pattern. Both traditional and formal residential areas are categorised as 'Compact midrise' from the LCZ system (LCZ 2) which includes a dense mix of midrise buildings (3-9 stories) with few or no trees and mostly paved land cover. As LCZ 2 only refers to uniform buildings, the traditional and formal residential areas are sub classified here as 'LCZ 2_Traditional' and 'LCZ 2_Formal'. Such subclasses are not identical to the ones currently available in the LCZ system, however, since the surface structure (height and spacing of buildings) of the sites are distinctly different, such grouping is necessary.

In total, six case study areas, which are representative of the city, have been chosen for the study (Figure 1-3). These include four residential case study areas: two LCZ_2_Traditional and two LCZ 2_Formal areas. The first two zones are called South Kafrul and Mid-Kafrul classified as LCZ 2_Traditional. These are mixed residential neighbourhoods with a combination of diverse building heights and building separations, mostly paved land cover and narrow streets. In the second site, the height variability is less and the streets are narrower. The two LCZ 2_Formal areas are called

Mahakhali DOHS and Baridhara DOHS. These are planned residential areas of uniform building heights (generally 6 storied apartments) with wider street widths.

Table 1. Abbreviated site names

	Microclimate site name	LCZ_classification	Abbreviated name
1	Traditional_1_South Kafrul_ East-West	LCZ 2_Traditional	TRA_1_EW
	Traditional_1_South Kafrul_ North-South	LCZ 2_Traditional	TRA_1_NS
2	Traditional_2_Mid Kafrul_ North-South	LCZ 2_Traditional	TRA_2_NS
3	Formal_1_Mahakhali DOHS_ East-West	LCZ 2_Formal	FRA_1_EW
4	Formal_2_Baridhara DOHS_ East-West	LCZ 2_Formal	FRA_2_EW
	Formal_2_Baridhara DOHS_ North-South	LCZ 2_Formal	FRA_2_NS
5	Commercial_Banani_ East-West	LCZ 1	CA_EW
6	Educational Area	LCZ 5	ECA
	Reference Zone: Bangladesh Meterological Department	LCZ 9	

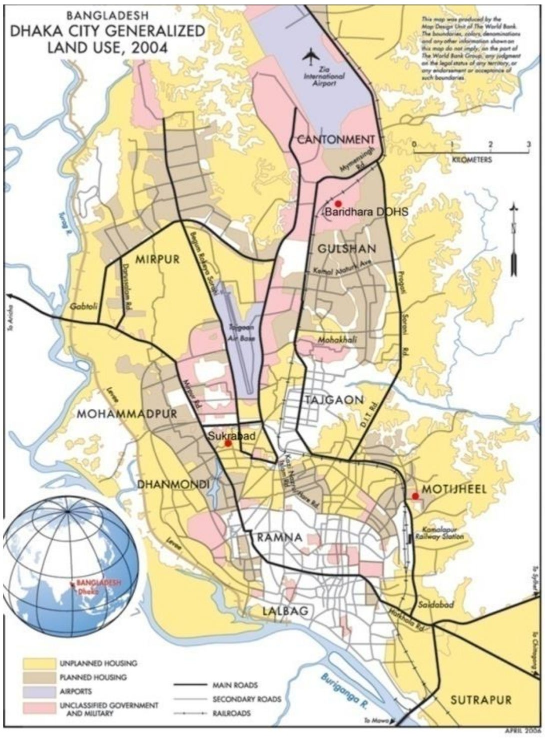


Figure 1. Zoning of planned and unplanned residential area in Dhaka, 2004, *World Bank*, *2006* [26]

Unplanned housing
Planned housing
Airports
Unclassified government & military

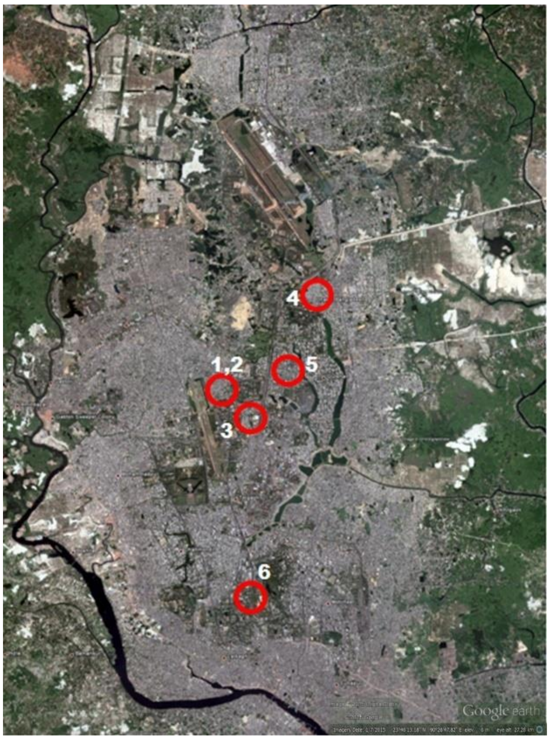


Figure 2. Location of the case-study areas in Dhaka city. Map data ©2015 Google Earth, Dhaka, Bangladesh. *Source:* “Dhaka”.23^{0}46’02.75” N and 90^{0}25’10.32” E. **Google Earth**. January 07, 2015. April 20, 2015. [27]

The fifth case-study area is a commercial area; compact high-rise (LCZ 1) with buildings more than 10 stories high and mostly paved land cover, few or no trees, high traffic and elevated pollution levels. The last case study area is an educational area with an open arrangement of midrise buildings (LCZ 5) with an abundance of pervious land covers (low plants and scattered trees).The buildings in such an area are mostly academic buildings and residential dormitories for the students and the staff. The study also uses Bangladesh Meteorological Department at Dhaka as a reference zone. The zone can be classified as sparsely built according to the LCZ system (LCZ 9). Each case study area is briefly described in Figure 4 (a, b, c) and a list of abbreviated names for each survey site is presented in Table 1.

2.3 Micro-meteorological monitoring and data

Meteorological monitoring and outdoor thermal comfort surveys were conducted during bright sunny rain-free days [1,12] in September 2014 for over a week, covering one case-study area per day at east-west and north-south orientations. In an east-west street measurements were taken on the north side of the street and in a north-south street on the east side of the street, as these are critical positions for solar exposure. The specific time period was chosen to include high temperature coupled with high humidity which makes outdoor spaces particularly uncomfortable. Another intension was to avoid the heavy rainy season over July and August, whilst still obtaining comfort responses during the hot-humid season.

Figure 3. Left: volunteers conducting surveys. Right: Instruments.

The measured climatic parameters include: air temperature, humidity, wind speed and globe temperature. Measurements were taken at several points in each site with one point remaining constant approximately at 1.1m height and at-least 1m distant from the nearby building (Figure 3). The measurement points were typically chosen around the middle of the length of the canyon to capture its microclimatic property. The specific height of 1.1m represents the gravitational centre for an average height human body [28].

Table 2 lists the name, range and accuracy of the instruments used in the study compared against ISO standards [29]. Tiny-Tag Data loggers were used to measure air temperature and humidity over a 9 hour period, spanning between 9am to 6pm. Wind speed was measured with a three cup anemometer at the same height (1.1 to 1.2m) recorded with an OM-CP-WIND101A data logger. Globe temperature was measured using a Tiny-tag data-logger with a thermo-couple thermistor probe. The globe consisted of a 40mm ping-pong ball painted in Humbrol matte grey. Air temperature, humidity and globe temperature data were measured at 5 minute intervals and wind speed at 1 minute intervals. Mean radiant temperature (Tmrt) is calculated based on the following formula [30]:

$$\text{Tmrt} = \left[\frac{(T_g + 273)^4 + (1.10 \times 10^8\, v^{0.6})(T_g - T_a)}{(\varepsilon D^{0.4})}\right]^{1/4} - 273$$

where Tmrt is mean radiant temperature (°C), T_g is globe temperature (°C), T_a is air temperature (°C), v is air velocity (m/s), D is globe diameter (m) (=0.04 m in this study) and ε is emissivity (=0.97 for flat grey-coloured globe). Operative temperature (T_{op}), which combines the effect of Tmrt and air temperature (T_a), was measured using the following formula [31]:

$$T_{op} = \frac{(T_{mrt} + (T_a \times \sqrt{10v}))}{1 + \sqrt{10v}}$$

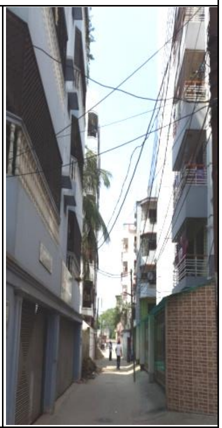
where v, Tmrt and T_a is same as the previous equation. Ambient temperatures measured during the survey days between 9:00am to 18:00pm ranged between 28.3 and 36.3^{0}C, with corresponding relative humidity ranging from 55to 82%, while the mean radiant temperature varied between 28.2 to 47.8^{0}C (Table 3). The average wind speed was 0.44 m/s.

Microclimate site name	LCZ_number	LCZ_ classification	Abbreviated name
Traditional_1_South Kafrul_ East-West and Traditional_1_South Kafrul_ North-South	LCZ 2_Traditional	Compact Mid-rise	TRA_1_EW and TRA_1_NS

Definition: Attached or closely spaced buildings of 3-9 stories high. Buildings are separated by narrow streets. Variable building heights and plot sizes. Sky view factor is significantly low at street level. Heavy construction materials (concrete, brick). Moderate space cooling demand. Moderate traffic flow.
Function: Residential (multi-unit housing; multi-storey tenements). ***Location:*** Core (inner city)

Illustration





Properties

Sky View Factor	Canyon Aspect Ratio	Building Height Range	Terrain roughness class	percentage of green	Percentage of built-up area
0.113 –0.331	1 – 4	10 – 29 m	6-7	<10%	70%-80%

Microclimate site name	LCZ_number	LCZ_classification	Abbreviated name
Traditional_2_Mid Kafrul_ North-South	LCZ 2_Traditional	Compact Mid-rise	TRA_2_NS

Definition: Attached or closely spaced buildings of 3-5 stories high. Buildings are separated by very narrow streets. Building heights and plot sizes mostly uniform. Sky view factor is significantly low at street level. Heavy construction materials (concrete, brick). Moderate space cooling demand. Moderate traffic flow.
Function: Residential (multi-unit housing; multi-storey tenements); commercial (grocery shops, cottage industry, small-scale local business). ***Location:*** Core (inner city)

Illustration



Properties

Sky View Factor	Canyon Aspect Ratio	Building Height Range	Terrain roughness class	percentage of green	Percentage of built-up area
0.133 –0.168	1.8 - 3.5	10 - 16m	6-7	<10%	70%-80%

Figure 4a. Microclimatic case study sites: LCZ_2_Traditional. Map data ©2015 Google Earth, Dhaka, Bangladesh [32]

Microclimate site name	LCZ_number	LCZ_classification	Abbreviated name
Formal_1_Mahakhali DOHS_ East-West	LCZ 2_Formal	Compact Mid-rise	FRA_1_EW

Definition: Attached or closely spaced buildings of 6 storied high. Buildings are separated by narrow streets. Uniform building heights and plot sizes. Sky view factor is low at street level. Heavy construction materials (concrete, brick). Moderate space cooling demand. Moderate traffic flow.
Function: Residential (multi-unit housing; multi-storey tenements), commercial (office buildings)
Location: Core (inner city)

Illustration


Properties

Sky View Factor	Canyon Aspect Ratio	Mean Building Height	Terrain roughness class	percentage of green	Percentage of built-up area
0.169 – 0.277	2 – 2.5	20 m	6-7	<10%	70%

Microclimate site name	LCZ_number	LCZ_classification	Abbreviated name
Formal_2_ Baridhara DOHS_ East-West and Formal_2_ Baridhara DOHS_ North-South	LCZ 2_Formal	Compact Mid-rise	FRA_2_EW and FRA_2_NS

Definition: Attached or closely spaced buildings of 6 storied high. Buildings are separated by slightly wider streets. Uniform building heights and plot sizes. Sky view factor is low at street level. Heavy construction materials (concrete, brick). Moderate space cooling demand. Moderate traffic flow.
Function: Residential (multi-unit housing; multi-storey tenements), commercial (office buildings)
Location: Core (inner city)

Illustration



Properties

Sky View Factor	Canyon Aspect Ratio	Mean Building Height	Terrain roughness class	percentage of green	Percentage of built-up area
0.229 – 0.259	1.2 – 1.8	20 m	6-7	<10%	60%

Figure 4b. Microclimatic case study sites: LCZ_2_Formal. Map data ©2015 Google Earth, Dhaka, Bangladesh [32]

Microclimate site name	LCZ_number	LCZ_classification	Abbreviated name
Commercial_ Banani_ East-West	LCZ 1	Compact High-rise	CA_EW

Definition: Dense mix of high-rise buildings over ten stories. Building are mostly attached or closely spaced. Building heights and plot sizes are mostly uniform. Sky view factor is significantly low at street level. Heavy construction materials (steel, concrete, brick, glass). High space cooling demand. Heavy traffic flow. ***Function:*** Commercial (office buildings, hotels), residential (apartment towers)**.** ***Location:*** Core (central business district)

Illustration

	Sky View Factor	Canyon Aspect Ratio	Building Height Range	Terrain roughness class	percentage of green	Percentage of built-up area
Properties	0.132 - .179	1.6 -2.75	32 – 62 m	8	<5%	80%

Microclimate site name	LCZ_number	LCZ_classification	Abbreviated name
Educational Area	LCZ 5	Open Mid-rise	ECA

Definition: Open arrangements of buildings 3-6 stories tall. Sky view factor is higher. Heavy construction materials (concrete, brick). Scattered trees and abundant plant cover. Low space cooling demand. Low traffic flow. **Function:** Institutional (research, campuses), residential (multi-unit housing; multi-storey tenements)
Location: Core (inner city)

Illustration

	Sky View Factor	Canyon Aspect Ratio	Building Height Range	Terrain roughness class	percentage of green	Percentage of built-up area
Properties	.447 - .756	0.3 – 0.75	10 – 20 m	5-6	20%-30%	50%

Figure 4c. Microclimatic case study sites: LCZ_1, LCZ_5. Map data ©2015 Google Earth, Dhaka, Bangladesh [32]

Table 2. Measuring range and accuracy for the instruments used

Instruments in the study		
Name of the current instrument	**Range of the current instrument**	**Accuracy of the current instrument**
Tinytag Ultra 2 Temperature/Relative Humidity Logger	(-25 to +85°C)/	Better than ±0.5°C
Tinytag Plus 2 Temperature Logger for Thermistor Probe PB-5001	(-40 to +125°C)	Logger: Better than ±0.35°C, when used with PB-5001
OM-CP-WIND101A-KIT Series-	0 to 100 MPH (0 to 44.704m/s)	±2.0 mph from 0 to 10 mph; ±2.5% of reading from >10 to 100 mph
Tinytag Ultra 2 Temperature/Relative Humidity Logger	0 to 95% RH	±3.0% RH at 25°C / 77°F

Table 3. Summary of the physical data of outdoor microclimate during survey days between 9:00am to 18:00pm

	Min	Max	Mean	SD
Air temperature, ^{0}C	28.3	36.3	31.7	1.67
Globe temperature, ^{0}C	28.3	42.9	32.3	2.98
Relative humidity, %	55	82	71	5.87
Wind speed, m/s	0	4.1	0.4	1.12
Mean radiant temperature, ^{0}C	28.2	47.8	32.7	4.32
Operative temperature, ^{0}C	28.4	38.9	32.2	2.23

2.4 Microclimatic analysis

The climatic conditions measured at each survey site were compared with the weather station data (reference data for each survey day) collected from the Bangladesh Meteorological Department at Dhaka. According to the weather station data, the survey days can be regarded as typical days when high temperature is coupled with high humidity, having high cloud coverage (average cloud coverage 5.5 okta).

To get a complete picture of the comfort situation in the streets, a whole day observation is used for each site. This reveals the relationships between urban geometry and variable climatic parameters throughout the day. The whole day questionnaire survey and climatic measurements were analysed in this study in order to study the relation between climate and thermal comfort. But, to get a comparative climatic picture of the sites, the simplest way was to compare them at the same period of the day. This has been done at this stage by comparing them between 12:00 to 3:00pm. This is the hottest period of the day when pedestrian comfort is more vulnerable. The air temperature data of the microclimate site along with weather station data is presented in Table 4.

2.5 Questionnaire Survey

A questionnaire survey was carried out along with physical measurements to understand the impact of urban geometry and thereby urban microclimate on pedestrian comfort. The survey includes over 700 interviews conducted across the case-study areas. The aim was to identify any discrepancy in thermal sensation responses in different urban configurations and recognize the possible reasons behind the difference. Information on the role of adaptation in thermal perceptions was collected in the survey but this topic is not covered in this paper. The questionnaire was prepared on the basis of previous research [33, 34] and a pilot survey conducted in August, 2012. For proper execution of the survey, the questionnaire was translated into the local language. Participants were asked about their thermal sensation, acceptability and preferences along with humidity, wind speed and solar radiation sensations. Physical attributes like age, gender, body-type and activity were noted. Clothing information was obtained from observation. A sample questionnaire can be found in Figure 5.

3. RESULTS AND DISCUSSION

3.1 Air temperature variation within microclimate sites

The average temperature of the survey days during this period as per the weather station data is 31.7^{0}C with a standard deviation of 1.5^{0}C (Table 4). This means there is no significant contrast among the survey days. Temperature ranges were between 27^{0}C to 33.5^{0}C throughout survey days at the weather station between 9am to 6pm. Lowest and highest average temperatures are observed on Day 3 and Day 5 respectively (Table 4). Accordingly, Day 3 can be regarded as the coolest and Day 5 the hottest day during the survey period. In the case of the microclimatic sites the standard deviation of the daily average temperature is also low (1.50, Table 4) suggesting that it is not the most appropriate parameter to understand deviations within each site. Hour by hour standard deviations and temperature ranges are better indicators to understand the variations between the sites (Table 5 and 6).

Table 4. Comparison of microclimate and weather station data between 12:00 to 3:00pm[2]

Survey Day	Average Air temperature: Weather Station Data (Standard Deviation)	Average Air temperature: Microclimate Data (Standard Deviation)	Difference: microclimate data - weather station data	Microclimate site name (abbreviate)
Day_1	31.5 (0.46)	31.2 (1.47)	-0.3	TRA_1_EW
Day_2	32.5 (0.64)	33.8 (0.88)	1.3	CA_EW
Day_3	29 (0.18)	30.7 (0.33)	1.7	FRA_1_EW
Day_4	31.5 (0.27)	34.1 (1.29)	2.6	FRA_2_EW
Day_4	31.5 (0.27)	32.6 (1.43)	1.1	FRA_2_NS
Day_5	33.5 (0.09)	32.9 (1.19)	-0.6	TRA_2_NS
Day_6	31.9 (1.37)	30.4 (0.84)	-1.5	ECA
Average Air temperature of the days	31.7	32.2		
Standard deviation of Air temperature between days	1.50	1.50		

From microclimatic measurements the lowest average temperature, in absolute terms and relative to the reference data, was at Educational Courtyard Area (ECA) (Table 4) due to its ground cover, open space, abundance of greenery and low building density. The next lowest average temperature was recorded on Day 3 at Formal Residential Area 1 (FRA_1_EW). Since this was the coolest of the survey days, this result was not unexpected. However, relatively this area had the second highest increase in temperature compared to the reference data. Similarly, Traditional Residential Area 2 (TRA_2_NS) was expected to have the highest average temperature as the survey on this site was conducted on the hottest day (on Day 5) with 33.5^{0}C average reference temperature. But, in contrast, this site had a lower average temperature (32.9^{0}C), 0.6^{0}C lower than the reference data. This is clearly an effect of microclimate, due to its narrow streets and high H/W ratio (3.5).

The highest average absolute and relative temperature is observed on Day 4 at the Formal Residential Area 2 (FRA_2_EW). This is also due to the effect of microclimate because the weather

[2] Average air temperature is the average of 4 readings (hourly) between 12:00-3:00 pm and standard deviation is calculated between these 4 readings.

station data on Day 4 shows a typical value. The area is characterised with uniform building heights and a comparatively lower H/W ratio (1.78).

In order to decide which site performs better in terms of microclimate, climatic variables (temperature, humidity and wind speed) from each site were compared with the same variables of the reference data (from the weather station) for that particular day. It is interesting to notice that both traditional sites (east-west and north-south orientations) had lower temperatures than the reference data. This suggests that the micro-climatic conditions of both traditional sites have an ameliorating effect on the synoptic climate. The formal residential sites, on the other hand, had higher temperatures. This indicates that such areas along with commercial areas have a tendency to develop a daytime urban heat island effect.

The highest air temperature is observed at Formal Residential Area 2 (FRA_2_EW) where the average difference in air temperature from the reference data is 2.6^0C. The corresponding north-south road has a smaller difference of 1.1^0C indicating that the north-south road direction performs better than the east-west road. Similarly in the Traditional area, the north-south road has more cooling (or less overheating) effect compared to the reference data than the east-west road. This is due to the fact that an E-W street is more exposed to daytime radiative loads than a N-S street of the same aspect ratio [35].

Considering the microclimate data, the best condition is found at Educational Courtyard Area (ECA) at Day 6 with a difference of -1.5^0C compared with the reference data. This has occurred due to the microclimatic conditions of the site. The next negative difference of -0.6^0C with the reference data has occurred on Day 5 at Traditional Residential Area 2 (TRA_2_NS). This suggests the microclimate of this site has helped to lower the actual temperature for the day.

Several studies in other climates (such as Ali Tuodert, 2005, in hot arid climate [36]) have identified that air temperature is less affected by geometry. However this study suggests a significant variation in air temperature exits between sites. According to Stewart and Oke [25], the variation can often exceed 5K between urban areas with significant diversity in geometry and cover, whereas deviation within urban areas with smaller physical variability can be less than 2 K. A comparison of hourly air temperature at the micro-climatic sites reveals a maximum difference of 6.2^{0}C occurring at 12:00 pm between FRA_2_EW and ECA (Table 5) and a minimum difference of 3^{0}C occurring at 15:00pm between CA_EW and FRA_1_EW. When excluding the effect of the coolest (Day 3) and hottest (Day 5) survey days, the comparison between the formal FRA_2_EW and traditional residential area TRA_1_EW, which have the same average synoptic air temperature patterns, shows 3.8^{0}C to 1^{0}C difference (Table 5).

Table 5. Average Hourly air temperature at microclimate sites[3]

Time	TRA_1_EW (SD_multi[4], [5])	CA_EW	FRA_1_EW	FRA_2_EW (SD_multi)	FRA_2_NS	TRA_2_NS (SD_multi)	ECA (SD_multi)	Max	Min	Range	Standard deviation of air temperature between different sites	Differences between TRA_1_EW and FRA_2_EW[6]
12:00:00	**32.7**(0.48)	**32.7**	**31.0**	**36.0**(0.43)	**34.6**	**34.2**(0.54)	**29.8**(0.11)	**36.0**	**29.8**	**6.2**	**2.15**	**3.3**
13:00:00	**29.8**(0.54)	**34.7**	**30.9**	**33.6**(0.37)	**32.6**	**33.2** (0.51)	**29.7**(0.55)	**34.7**	**29.7**	**5.0**	**1.95**	**3.8**
14:00:00	**30.0**(0.29)	**34.2**	**30.5**	**33.7**(0.50)	**31.7**	**32.8**(0.92)	**31.4**(1.47)	**34.2**	**30.0**	**4.2**	**1.58**	**3.7**
15:00:00	**32.1**(0.55)	**33.3**	**30.3**	**33.2**(0.32)	**31.5**	**31.8**(0.77)	**30.9**(0.09)	**33.3**	**30.3**	**3.0**	**1.11**	**1.0**

Large differences were identified in terms of mean radiant temperature across the case-study areas. The highest difference of 15.2^{0}C was observed at 12:00pm between the ECA and FRA_1_EW and the smallest difference of 4.4^{0}C between CA_EW and FRA_1_EW (Table 6). This is governed by the solar radiation pattern within the sites that is basically modified by the urban geometry. Mean radiant temperature (Tmrt) is higher in areas that are exposed to direct solar

[3]Air temperature was measured at 5 minute intervals and each hourly value is the average of previous 12 readings
[4]Standard Deviation between multiple measurement points.
[5]Standard deviations of Air-Temperature for each site are presented where this is an average of multiple measurement points. For the microclimatic sites where a single measurement is used, the standard deviation is not included. Although air temperature and humidity were measured at multiple locations in each site, not every point represented the outdoor climatic conditions: for example recordings in semi-outdoor spaces like a ground floor garage or corridors were excluded from calculation.

[6] excluding the effect of the coolest (Day 3) and hottest (Day 5) survey days and including the days that have similar average from the weather station data

Questionnaire Survey
Outdoor Thermal Comfort Analysis

Date:		**Time:**	
Name of the venue:		**Street orientation:**	
Type of venue: Formal Residential Area Traditional/informal Residential Area	Commercial Area Educational Area	**Name and the contact of the person conducting the survey:**	

Gender:		○ Male		○ Female
Age:	Teenager	Young	Middle -aged	Old
Body Type:	Skinny	Normal	Obese	

Activity (Met):	**Activity**	**Heat produced in watts**
	○ Sitting	130-160
	○ Standing, light work	160-190
	○ light walking	220-290
	○ Moderate walking	290-410

Is the subject's head/body exposed to direct sunlight?	Yes	No

Clothing

.1	.2	.3	.4	.4	.5	.5	.7	11	.3	.4	.5	.5	.6	.7	.9	1.2

Length of time living in Dhaka: (years)	Below 1 year	Below 5 years	Above 5 years
Profession:			
Profession nature:	○ Indoor type	○ Outdoor type	
In the past 30 minutes, prior to the survey, have you been to (or stayed in) any air-conditioned indoor space?	○ Yes	○ No	
Have you been travelling in the past 30 minutes?	○ Yes	○ No	

Mode of travelling:	Bus	Car/ Taxi	CNG	Rickshaw	Walking
What were you doing in the past 30 min prior to the survey?	Sitting	Standing	Working (Light)	Working (Moderate)	Working (Heavy)

Thermal sensation on traditional ASHRAE 7-point scale :	-3 cold	-2 cool	-1 slightly cool	0 neutral	+1 slightly warm	+2 warm	+3 hot

Thermal preference on 3-point McIntyre scale:	Prefer warmer	Prefer no change	Prefer cooler
Thermal acceptability assessment:	Acceptable	Unacceptable	

Humidity sensation vote on 5-point scale:	Too dry	Dry	OK	Humid	Too humid
Wind speed sensation vote	Still air	Little wind	OK	Windy	Too much wind
Solar radiation sensation vote	Too weak	Little weak	OK	Little strong	Too strong
How is your skin, in terms of wettedness?	Drops of sweat	moist	just right	dry	very dry
Why did you choose to sit/stand at this particular place? (can choose more than one item)	To take rest and enjoy environment(sun-shine,breeze, nice view)	Close to home, office, school or station	For no particular reason	Prefer not to say	Others: please mention
What adaptive behaviour would you like to adopt if there was a scope?	Move to shaded trees/ shelter	Open umbrella or wear hat	Get more drink	Reduce clothing	Nothing/ go away

Figure 5. Sample question

radiation [36]. Since solar exposure of the street canyon is a function of its geometry, Tmrt is also affected by this.

Table 6. Average hourly mean radiant temperature at micro-climate sites

Time	TRA_1_EW(SD-Standard deviation)[7]	CA_EW (SD)	FRA_1_EW (SD)	FRA_2_EW (SD)	FRA_2_NS (SD)	TRA_2_NS (SD)	ECA(SD)	Max	Min	Range	Standard Deviation between different sites
12:00	**30.9** (0.78)	**33.4** (0.69)	**29.8** (0.30)	**32.9** (1.49)	**34.6** (1.90)	**31.9** (0.25)	**45.0** (2.98)	**45.0**	**29.8**	**15.2**	**5.09**
13:00	**29.3** (0.46)	**33.4** (0.69)	**28.9** (0.31)	**31.6** (0.33)	**32.5** (0.47)	**31.9** (0.23)	**40.6** (5.78)	**40.6**	**28.9**	**11.7**	**3.89**
14:00	**29.2** (0.74)	**33.2** (0.62)	**28.7** (0.32)	**32.5** (0.34)	**32.5** (0.52)	**31.6** (0.18)	**29.7** (1.98)	**33.2**	**28.7**	**4.4**	**1.80**
15:00	**31.4** (0.25)	**32.4** (0.39)	**28.9** (0.39)	**32.1** (0.39)	**32.4** (0.50)	**31.4** (0.15)	**35.4** (4.38)	**35.4**	**28.9**	**6.4**	**1.91**

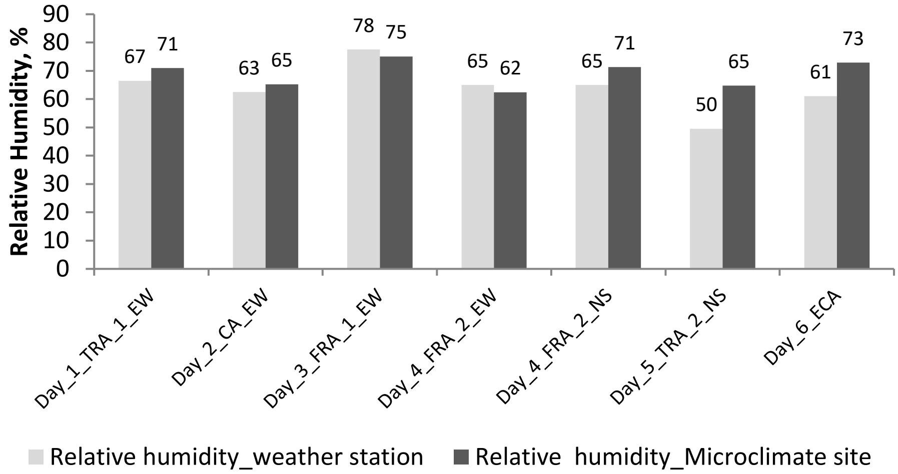
3.2 Humidity variation within microclimate sites

The average humidity of the microclimatic sites was 69% corresponding to an absolute humidity of 23.6 g/m^3 against 64% (21.2 g/m^3) in the weather station data. During the survey period (12:00 to 3:00pm), the lowest average absolute humidity of 22.9 g/m^3 was recorded at TRA_2_NS as an effect of the hottest survey day and also at TRA_1_EW (Figure 6a, 6b). Again, maximum differences of 15% (5 g/m^3), 12% (2.5 g/m^3) and 6% (3.5 g/m^3) between the microclimate site and the reference site humidity data is observed on Day 5, Day 6 and Day 4 in Traditional Residential Area 2 (TRA_2_NS), Courtyard Area (ECA) and Formal Residential Area FRA_2_NS respectively.

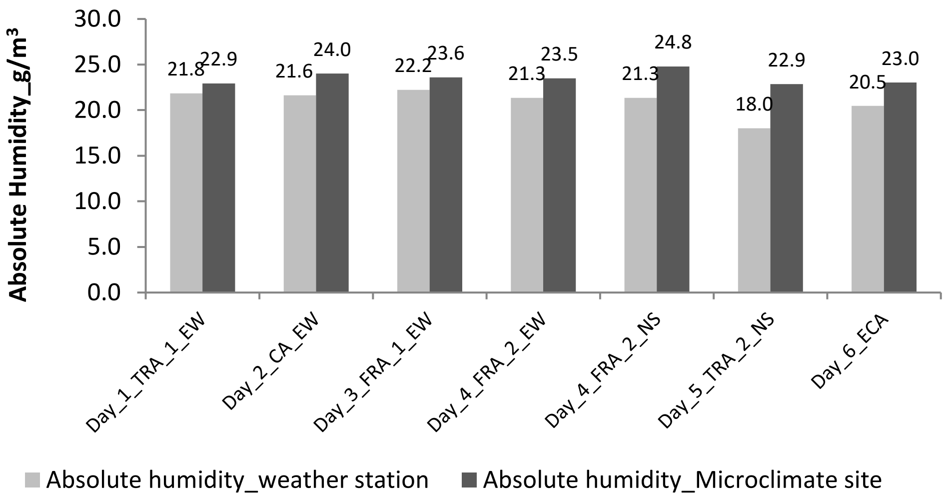
The rest of the sites, CA_EW, FRA_2_EW and FRA_2_NS shows slightly higher absolute humidity levels (24, 23.5, 24.8 g/m^3 respectively) than other sites creating critical comfort situations when coupled with their high temperature levels. The absolute humidity of 23.6 g/m^3 at

[7]Tmrt was calculated using globe temperature at 5 minutes interval and each hourly value is the average of previous 12 readings. Standard deviation between these 12 readings is presented in the table. Globe temperature was measured at single points where comfort vote was collected. Standard deviations are higher when the measurement point is subjected to direct solar radiation.

FRA_1_EW is assumed to be less problematic in terms of thermal comfort due to its lower air temperatures. The high humidity range, although considered normal in a hot-humid climate, can be a crucial factor for pedestrian comfort, especially, when exceeding the local comfort limit of 70% relative humidity at an air temperature between 28.5^{0}C to 32^0 C [16].



(a)



(b)

Figure 6.Difference between microclimate and weather station data. (a)Relative Humidity, (b) Absolute Humidity

In this study the absolute humidity (AH) in each microclimate site was found to be lower than the weather station data, whereas cities are typically considered to be drier (specially in terms of relative humidity) than the surrounding countryside. However, as far as vapour pressure (VP) and absolute humidity are concerned, they are in some cases higher in the cities. A climatic study on outdoor thermal comfort in Pune city [37] has reported rising moisture levels in the urban atmosphere. The reason for VP and AH being higher in the cities is related to turbulence and air exchange issues [38]. VP and AH have two maxima during the day: one during the first part of the day before convection starts. After convection starts, humidity tends to drop because of increased vertical exchanges. Then when convection is reduced, humidity increases again. This means in a microclimatic site, with less convection, VP and AH can be higher during the midday hours. In the current study microclimatic variables were compared only during a specific period of the day between 12:00 to 3:00 pm when solar altitude is high in the sky. The comparison of the whole day humidity pattern may yield different results. We could also hypothesize that the poor drainage system in Dhaka city may cause water to lie around longer, whereas in the developed cities the water runs away quickly due to more efficient drainage system. The area where weather station is located may well have a better drainage system than the microclimatic sites. There could be other reasons, such as inside the narrow urban canyon system in cities, combustion of fossil fuel in vehicular traffic could act as local source of water vapour and pollutant, "latter acting as hygroscopic nuclei in the process of condensation" [39]. This is explained by Oke (1978) [40]: "in the city less evaporation, reduced dewfall, anthropogenic vapour and the stagnation of airflow all combine to maintain a more humid atmosphere in the canyon air volume". This means cities can have a 'moisture island' in association with a 'heat island'.

3.3 Wind speed variation within microclimate sites

All microclimate sites apart from Traditional Residential 1 (TRA_1_EW) and Educational Courtyard (ECA) show significantly lower wind speeds in comparison to the reference site (Figure 7). This indicates that wind speed is unhelpfully low to mitigate high temperatures. Previous studies also suggest urban ventilation is inversely related to the density of a given area [41]. Along with the high density, other urban-geometry parameters such as the uniform height of buildings and their orientation perpendicular to the wind direction also worsen urban ventilation in Dhaka city. For example, on day 4, wind speed ranged from totally calm to 2.6 m/s on the reference site. But the case study site on the same day (FRA_2_EW) shows still air conditions throughout.

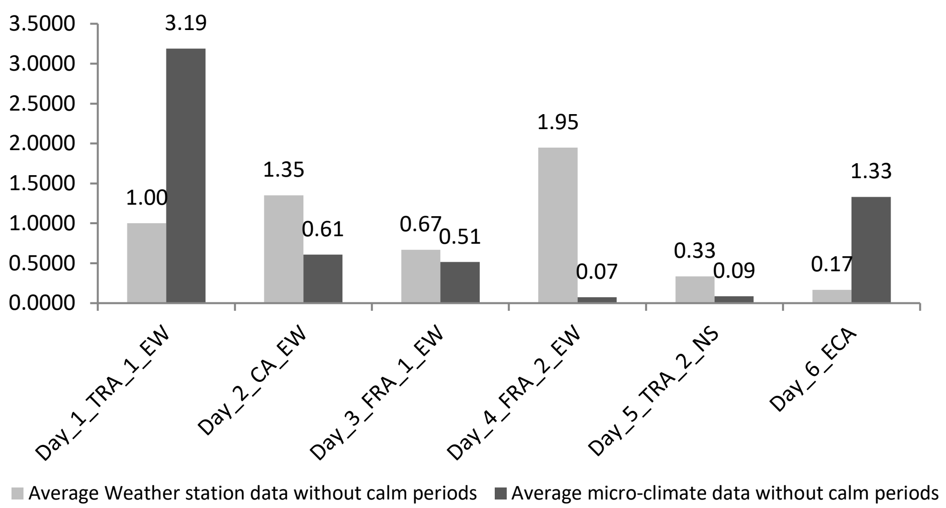


Figure 7.Comparison of average wind speed data between microclimate and reference site (weather station) during 12:00 to 3:00pm.

However, there are particular reasons for the wind speed being high at some microclimate sites. Height variability in Traditional Residential 1 (TRA_1_EW) plays a role in creating higher turbulence around the high-rise buildings next to the measurement site. Findings from Givoni (1998) [41] also suggest that "An urban profile of variable heights, where buildings of different height are placed next to each other, and when the long facades of the building are oblique to the wind, actually enhances urban ventilation." The direction of wind during the survey days was predominantly north and the next prominent direction was south (on Day 2, 4 and 5). On Day 1, the streets in question were aligned with the wind direction. Proximity to an abandoned airport may have encouraged further increase in the wind speed. Higher wind speeds were also recorded in the Educational Courtyard (ECA) site. This site is located in a low density area and wind speed was measured at the centre of a large courtyard where the recorded wind speed was higher than the reference site.

3.4 Correlation between urban geometry parameters (aspect ratio and SVF) and climatic variables

In order to check how far urban geometry affects urban microclimate, common geometric parameters such as H/W Ratio (Building height/ Street width) and SVF (Sky View Factor) were compared with each climatic variable using the statistical package, R. For correlation analysis

Pierson’s r coefficient (for normally distributed data) and Spearman’s rho coefficient (for skewed data) were used. Although, the correlation of both SVF and H/W ratio was analysed, SVF was chosen over H/W ratio, mainly because of variability of height in the traditional residential areas. The SVF, defined by the amount of sky visible from a particular point in the street, was calculated in a mathematical model using a microclimate simulation tool: Rayman Pro[42]. Using the site information, models were constructed in RayMan Pro and SVF was calculated at 1.1m height around the middle of the length of the canyon. For completeness, H/W Ratio was calculated manually using the average building height of the case study area and average street width.

Due to the variability and complexity in the urban form in the case-study areas, two more metrics were proposed that represent compactness as suggested by Bourdic et al [43]. These are Surface to Volume Ratio of the surrounding buildings (Volumetric Compactness= $\frac{\text{Building Surface (S)}}{\text{Building Volume (V)}}$ $=\frac{S}{V}$) and the Form Factor ($\frac{S}{V^{\frac{2}{3}}}$). Compactness ($\frac{S}{V}$), although recognised as a crucial indicator for energy needs in urban areas, identifies details of the morphology of buildings, streets and urban networks [43]. This makes it particularly suitable for use in this study. Form Factor was proposed to remove the bias introduced by the different size of the analysed objects. In this study, a better correlation was observed by including open ground surfaces along with building surfaces. Therefore, a third metric: Surface (including plot-size) to volume ratio ($\frac{S+Plot}{V}$) was used. Urban geometry metrics of the microclimate sites are listed on Table 7.

Two options were assessed, one including only residential cases and excluding commercial and educational areas and the second including all case-study areas. The reasons for analysing two options are to identify any variation occurring due to land-use pattern as well as geometry of the urban areas. Both options yield moderate to very strong correlation among geometry parameters and climatic variables (Table 8). However, it is interesting to notice that air temperature and humidity correlations are opposite in two options.

Table. 7. Urban geometry metrics of the microclimate sites

Site_abbreviated	H/W_ratio	SVF	Surf2Vol_ratio	Surf2Vol_ratio_incl_plot area	Form_Factor
TRA_1_EW	2.57	0.177	0.245	0.256	8.74
TRA_1_NS	2.46	0.231	0.275	0.300	10.92
TRA_2_NS	3.5	0.149	0.357	0.380	11.61
FRA_1_EW	2.436	0.201	0.302	0.323	13.18
FRA_2_EW	1.78	0.229	0.325	0.404	11.19
FRA_2_NS	1.215	0.259	0.305	0.355	11.42
CA_EW	2.4	0.141	0.132	0.145	10.14
ECA	0.3	0.447	0.613	0.755	15.49
Standard Deviation	0.97	0.097	0.137	0.177	2.02

In Option 1, concerning the residential areas only, air temperature and humidity shows moderately strong correlation, (r = 0.449 and r = - 0.323 respectively) with compactness ($\frac{S}{V}$). This means, air temperature increases and humidity decreases as the amount of urban surfaces increase and compactness reduces. Air temperature follows a similar pattern in relation to H/W ratio and SVF, indicating its reduction in deeper urban canyons. This seems to be an obvious phenomena and the land-use pattern in the residential areas does not seem to have an effect on this. No correlation was found between SVF and humidity.

In Option 2, a completely opposite trend is visible in terms of correlation between air temperature, humidity and urban geometry. The relations are moderately strong (r =-0.37 between air temperature and Form Factor). This has mainly resulted from the inclusion of the commercial area CA_EW in the analysis which has a distinctive urban geometry with the lowest SVF (0.141) and highest compactness (or low surface to volume ratio) ($\frac{S}{V}$=0.145) level among all sites (Table 7). Micro-climatic analysis of the site also shows its average air temperature (33.8^{0}C) is higher than most other sites except FRA_2_EW (Table 4). The site also has a UHI tendency with its average air temperature being 1.3^{0}C higher than the synoptic climate data (Table 4). Not only does the geometry of the site sharply contrast with other sites, but also the usage is different. The anthropogenic heat release (fumes from motor cars and airconditioning units) is assumed to be higher than other sites since it is a commercial centre with air-conditioned buildings. Therefore, it is assumed, even though the mutual shading in the urban canyon is able to cut down significant amount of solar radiation, UHI impact due to anthropogenic heat release as well as increased reflected radiation from the built-up areas due to compact geometry has resulted in higher air temperatures in this area.

Table 8. Correlation between urban geometry parameters[8] :
Aspect ratio (H/W ratio), SVF and Surface to Volume Ratio and climatic variables

	Option 1(includes only residential sites and excludes commercial and educational areas)					**Option 2(includes all case-study sites)**				
Variable	**COR_ H/W_ratio_new**	**COR_ Sky view factor**	**COR_ Surface to volume ratio**	**COR_ Surface (inclplotsize) to volume ratio**	**COR_ Form factor**	**COR_ H/W_ratio_new**	**COR_ Sky view factor**	**COR_ Surface to volume ratio**	**COR_ Surface (incl plot-size) to volume ratio**	**COR_ Form factor**
Air temperature	-0.217 *p-value=* 0.00297	0.424	0.380	0.449	-0.298	0.167 *p-value=* 0.00805	-0.257	-0.348	-0.299	-0.37
Humidity	-0.218 *p-value=* 0.00284	null	-0.298	-0.323	0.409	-0.248	0.233	0.227	0.206	0.381
Globe-temperature	-0.401	0.648	0.242	0.363	-0.243	-0.387	0.378	0.256	0.298	0.241
Mean radiant temperature	-0.422	0.665	0.273	0.418	-0.268 *p-value=* 0.0015	-0.429	0.423	0.331	0.367 p-	0.305
Operative temperature	-0.382	0.617	0.296	0.378	-0.168 *p-value=* 0.0108	-0.321	0.259	0.29 *p-value=* 0.0057	0.174 *p-value=* 0.0057	0.203 *p-value=* 0.0057
Windspeed	0.443	-0.243	-0.833	-0.832	-0.543	0.293	null	-0.318	-0.317	-0.25

As far as globe temperature (GT), mean radiant temperature (Tmrt) and operative temperature (T_{OP}) are concerned, they all show positive and strong correlations with SVF, S/V and S+Plot/V and negative correlations with H/W ratio, in both options. This suggests that GT, Tmrt and T_{OP} will reduce in a deep or narrow street canyon and in a compact area. The correlation is particularly strong in Option 2 between the SVF and GT (r=0.648), SVF and Tmrt(r=0.665) and SVF and T_{OP} (r=0.617). Previous studies [44] have reported similar correlations between SVF and Tmrt (R^2= 0.3179 and 0.6093).

[8]All correlations are significant ($p < 0.0001$) unless otherwise mentioned.

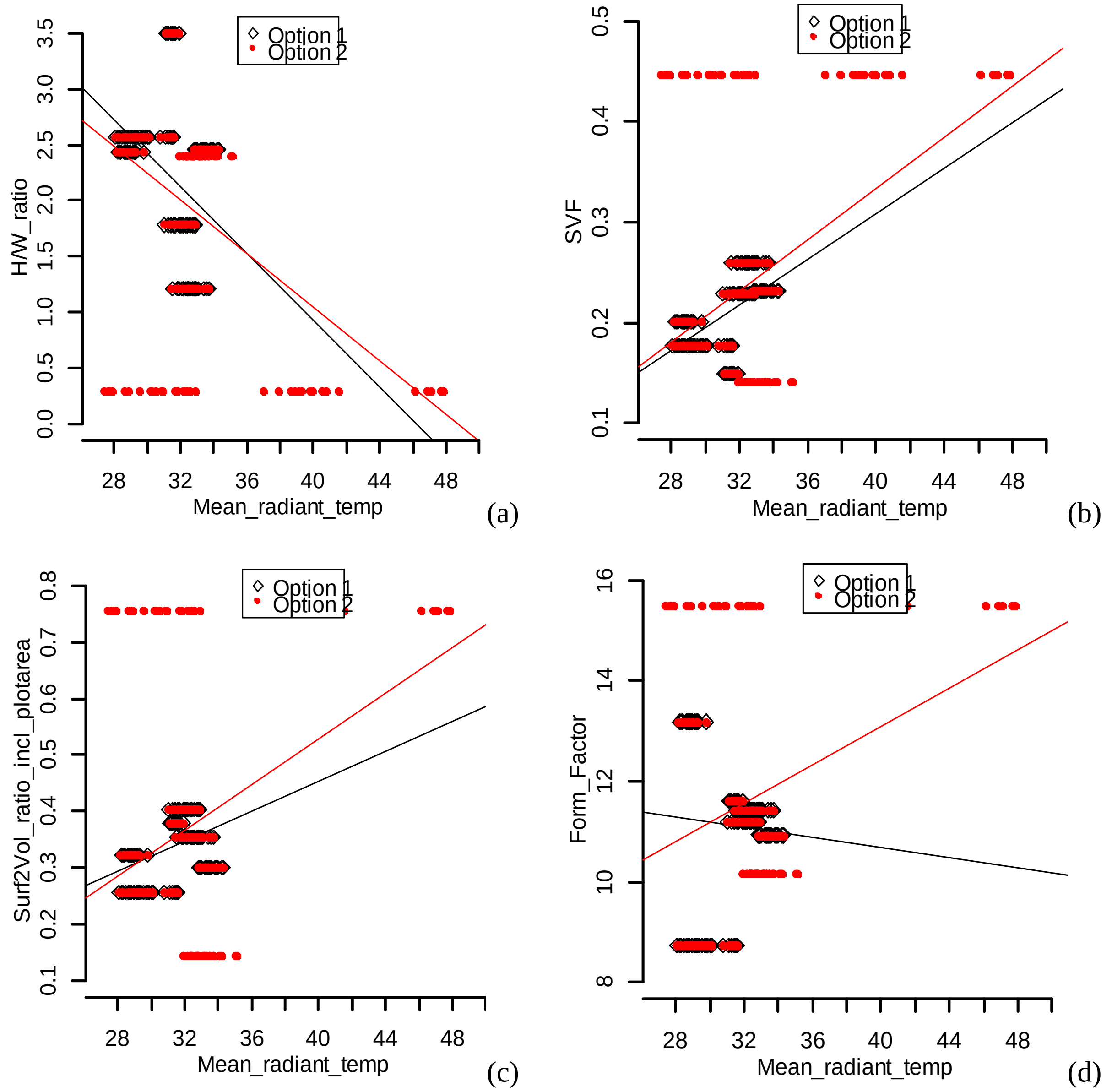


Figure 8. Scatter plots showing correlations between mean radiant temperature and urban geometry parameters in Option 1 and Option 2: a) With H/W ratio, b) With H/W ratio, c) With Surface (incl plot-size) to volume ratio and d) With Form Factor

The only exception is Form Factor ($S/V^{2/3}$) in Option 1 which shows negative correlations with the above parameters. It suggests that Form Factor is not an ideal parameter to address the variation in microclimate for urban forms which have mostly homogeneous geometry and land-use patterns as found in residential areas. However, it can be a really strong indicator for urban areas having more variety in form.

H/W ratio, S/V, S+Plot/V and Form Factor ($S/V^{2/3}$) show similar trends with the wind speed, while the correlation with SVF produces a null result in Option 2. Option 1 shows a better (very strong) correlation with surface to volume factors. This suggests that wind speed will increase in deeper canyons and in compact areas due to greater turbulence as observed during the survey.

From the above analysis it is apparent that S/V, S+Plot/V and Form Factor ($S/V^{2/3}$) are better indicators for air temperature and humidity in urban areas and may thus be better suited to energy performance and indoor comfort studies. H/W ratio and SVF, on the other hand, are good indicators for the radiant temperature parameters, such as, GT, Tmrt and OP and therefore, will be more applicable in outdoor thermal comfort studies.

3.5 Thermal comfort analysis

3.5.1 Impact of urban geometry on Thermal Sensation

In this study, people's thermal sensation was reported on a 7-point scale, ranging from "cold" to "hot", collected though a questionnaire survey. The middle point "neutral" represents a state of comfort. This is defined as the Actual Sensation Vote (ASV) or commonly known as subjective thermal sensation vote (TSV) [45]. Analysis of collected data through statistical correlation analysis reveals the correlations between microclimatic parameters and ASV (Table 9).

As the air temperature and globe-temperature in the site increases, ASV also increases towards hotter sensations. The correlation between them and ASV is moderately strong ($r = 0.288$ and 0.340 respectively) and significant. The correlation between humidity and ASV is found to be negative($r= -.317$), as is the correlation between wind speed and ASV ($r= -0.267$). This means that when humidity or the wind speed increases, ASV decreases and goes towards more comfortable sensations.Villadiego and Velay-Dabat (2013) [1] has reported similar correlations with air temperature ($r= 0.133$; 0.305), however humidity correlations were lower ($r = -0.1167$) and a null correlation was reported with wind speed. Nikolopouloua and Lykoudis (2006) [46], for their study across different Europian countries revealed that ASV correlates better with globe temperature ($r=0.53$) than air temperature ($r=0.43$), as also found in the current study. Considering, this is a hot-humid situation, the relation between humidity and ASV is rather confusing. However, we are talking about a high range of air temperatures here (range 28.3^0C to 36.3^0C) and any increase in relative humidity is associate with a decrease in air temperature as they are inversely correlated (r=-0.893). So, this explains why ASV decreases when humidity increases. In other words, humidity is an inversely correlated co-variable with temperature. Other studies in similar climates [1] have also reported negative correlations between ASV and relative humidity (r = -0.1167).

Table 9 Correlation between climatic variables and actual sensation vote (thermal sensation)[9]

Climatic variables	Correlation with ASV_all site
Air temperature	0.288
Humidity	-0.317
Globe temperature	0.340
Mean radiant temperature	0.385
Operative temperature	0.401
Windspeed	-0.267

Table 10. Percentage of thermal sensation

Thermal sensation	Number of people	Percentage of people (%)
Cold	0	0
Cool	0	0
Slightly cool	10	2
Neutral	106	19
Slightly warm	220	40
Warm	148	27
Hot	68	12
Total	552	100

Thermal sensation and preference votes were collected from the pedestrians in the case-study areas from 9:00am to 6:00pm. The intention was to see how people behaved in response to the microclimatic conditions in the street. Analysis from the database (Table 10) showed that the maximum proportion of people (40%) during the survey felt 'Slightly Warm' with a portion feeling 'Warm' (27%) and 'Hot' (12%). Less than one fifth of the population (19%) reported feeling comfortable or neutral. This suggests people found the weather conditions during the survey period significantly above the comfort level. This is not surprising as the fact that the air temperature during the survey period ranged between 28.3 to 36.3^{0}C with an average of 31.7^{0}C. The average wind speed during this period was 0.44m/s with an average relative humidity of 70.50%.

For the hot-humid climate of Dhaka, comfortable temperatures for outdoor conditions ranges from 28.5^{0}C to 32^0 C at an average relative humidity of 70% under still air conditions for people wearing typical summer clothes (0.4 to 0.5 Clo) and involved in sedentary activities [16]. During

[9]All correlations are significant (p < 0.0001) unless otherwise mentioned.

the survey period temperature was equal to or above 32^{0}C (below 37^{0}C) almost 40% of the time. This explains the reason for most people feeling 'slightly warm' and a significant percentage feeling 'warm' and 'hot'. What is interesting is that almost 88% of subjects found the climatic conditions to be acceptable, whereas only 12% thought this was unacceptable. This suggests a high tolerance of high temperature amongst pedestrians in tropical cities. Previous studies also support this finding [47].

Although the climatic conditions were acceptable to most of the people, 74% of the total population preferred cooler temperatures, whereas 26% of people who wanted to keep up with the same air temperature. This indicates even though people have acclimatised to high temperatures, they are only partially satisfied.

Among those feeling neutral or comfortable, 67% people preferred no change, while only 30% preferred a cooler ambience. This is in contrast with McIntyre's findings (1980, cited in [1]) that established that people feeling neutral in warm climates would prefer to be cooler. This suggests that people's thermal preference depends on their expectation and adaptation levels in a specific climatic and cultural context.

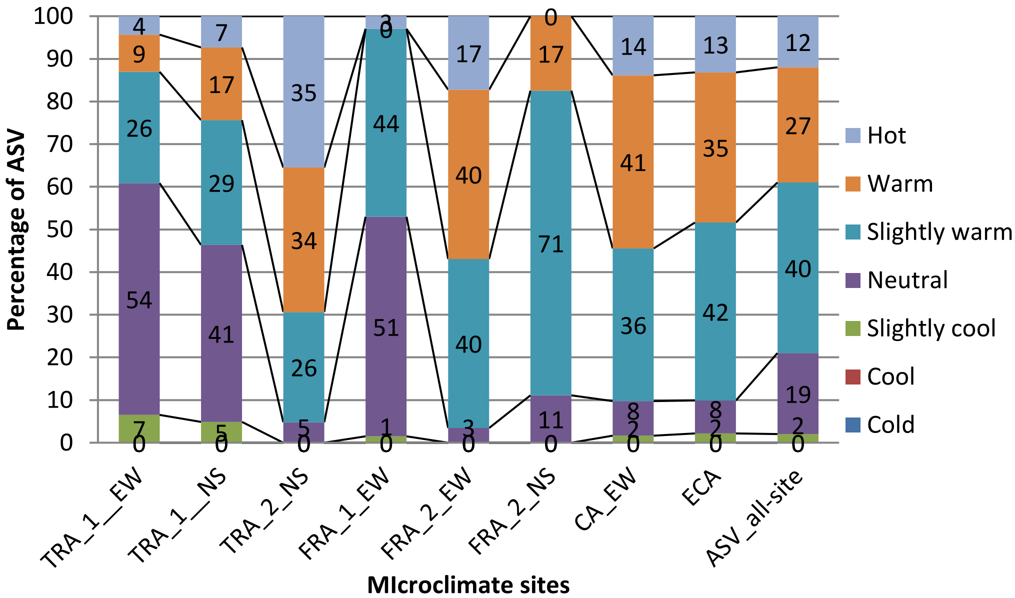


Figure 9. Percentage frequency for the ASV across different sites

Table 11. Peak ASV values for microclimate sites	
Site_abbreviated	**Peak ASV value**
TRA_1_EW	Neutral
TRA_1_NS	Neutral
TRA_2_NS	Hot
FRA_1_EW	Neutral
FRA_2_EW	Slightly warm/Warm
FRA_2_NS	Slightly warm
CA_EW	Warm
ECA	Slightly warm

Analysis of individual case-study areas showed a variety of thermal sensations across the sites, different from the general ASV pattern (Figure 9). The overall ASV shows a majority of ‘slightly warm’ sensations, and only two sites (FRA_2_NS and ECA) show a similar preponderance (Table 11). On the other hand, sites CA_EW and FRA_2_EW results incline predominantly towards ‘warm’ or ‘hot’ sensations (Table 11). The sites, although being quite compact, lacks in diversity, having similar building heights and plot sizes. Due to the tropical location of the study area, even the compact areas cannot escape high solar penetration, especially during the noon. Uniform heights and straight streets produce a linear and almost uniform pattern of shade throughout the street. That means when a street is open to the sun, the whole length of it is exposed without any shade. In a traditional area, on the other hand, H/W ratios vary at different points in the same street, creating a network of shaded areas. However, although being a traditional site, the site TRA_2_NS was reported ‘Hot’ because it is less diverse and less variable with the lowest compactness among most other sites (Table 7,Surf2Vol_ratio= .357). It consisted of building and plots of similar sizes. For this reason, the shadow pattern in the street was also mostly uniform and could not offer pedestrians much shading. The fact that the survey on this site was conducted on the hottest survey day has exaggerated the impact on ASV.

The sites that show predominantly ‘neutral’ sensations or are mainly comfortable are TRA_1_EW, TRA_1_NS and FRA_1_EW. The last one being a formal residential area, FRA_1_EW, was found comfortable only due to the fact that this was examined on the coolest of the survey days (Day 3). It is evident that variability in urban form can contribute to positive changes in the thermal sensation of pedestrians.

4. Conclusions

The overall thermal response for the whole sample demonstrates that 79% of subjects voted ‘slightly warm’, ‘warm’ or ‘hot’, while 21% were ‘neutral’ and cooler. Most people (40%) were found to be feeling ‘slightly warm’. Considering the high temperature and high humidity range (DBT 28.3^{0}Cto 36.3^{0}C and RH 55% to 82%) during the survey period, this result is slightly higher than expected but not unreasonable. Despite this fact, the apparently unfavourable thermal conditions were nevertheless reported as being acceptable to 88% of people, suggesting a tolerance for high temperatures amongst pedestrians in tropical cities. Pedestrians were found to be more comfortable in deep and compact urban areas with variability and diversity of form, supporting earlier speculation [48] and confirming the significance of urban geometry for outdoor thermal comfort.

Analysis in this study also explains that variation in urban form can bring about positive changes in the urban microclimate. The diversity in building heights, street patterns and the overall configuration of urban canyons can create a network of shaded spaces and increase urban ventilation to some extent, resulting in an average reduction in daytime temperature below synoptic conditions and significantly below other areas of the city. This phenomenon was observed in the traditional case study areas: TRA_1_EW and TRA_1_NS, having deep canyons and more variability. The other traditional areaTRA_2_NS, having deep canyon was also able to lower the synoptic climate to some extent, but was unable to create a comfortable microclimate due to its lesser compactness and unvarying character. Formal residential and planned areas, on the other hand, with uniform characters, are susceptible to higher solar radiation and poorer ventilation. These factors resulted in higher average daytime temperatures in comparison to the traditional areas by approximately 4^0C. The planned areas also showed a tendency to develop a daytime urban heat island effect.

The statistical analysis between the geometry parameters and climatic variables revealed that urban geometry has a significant impact on urban microclimate and thereby, on outdoor thermal comfort sensations. It reveals moderate to very strong correlations between the urban geometry and climatic variables. The main parameters for urban geometry were H/W ratio, SVF, Surface to Volume ratio (including or excluding plot areas) and Form Factor. Surface to Volume ratios and Form Factors were found to be better indicators for air temperature and humidity, thereby, could be useful to study the impact of urban microclimate on indoor comfort and building energy performance. H/W ratio and SVF, on the other hand, were better indicators for GT, Tmrt and T_{op}, which are more relevant to outdoor thermal comfort. The Form Factor was identified to be more applicable for urban areas with heterogeneous characters. To conclude, the results and information from this study can be integrated in the future urban planning processes for improving urban microclimate and thermal sensation through the modification of urban forms.

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