Study on Thermal Environment and Comfort of Indoor and Outdoor Spaces on University Campus in Tropical Climate in Dhaka, Bangladesh

by

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Abstract

Thermal environment and comfort affect human health, and productivity considerably. The teaching and learning activities are directly related to the thermal environment in university spaces. This study is an attempt to evaluate the thermal environment and comfort in university spaces, Dhaka, Bangladesh, conducted by field measurement-based investigation and computer program-based simulation. The field measurement was carried out in the typical hot summer days between May and June in different indoor and outdoor university spaces. Field measurement was conducted on daytime only to measure air temperature, relative humidity, globe temperature, air velocity, solar irradiation. Comfort index (SET*) has been calculated based on measurement weather data. The filed measurement results indicate that the indoor weather parameters e.g., air temperature, relative humidity approach in a steady manner as the time progresses. The outdoor weather parameters, on contrary, fluctuated in a greater extent. The outdoor air temperature and air velocity were recorded higher than their indoor counterparts.

The indoor thermal environment corresponds to those surrounding outdoor weather parameters. The outdoor air temperature of more tree area was found lower than the air temperature of area with less tree. In response to the outdoor condition, air temperature in the classroom surrounded by more tree area was found lower than in the classroom surrounded by less tree area. Moreover, the outdoor air temperature near the lakeside classroom was also found lower than the outdoor space of non-lakeside classroom. However, the indoor air temperature of the lakeside classroom was not lower than non-lakeside classroom since the lakeside classroom is located on the top floor and gain more heat. The non-lakeside classroom was located 3rd floor of a four-storied building and thus less exposed to the direct heat gain.

The impact of the weather parameters especially air temperature and air velocity were notable on the comfort index. As a result, the outdoor SET* values fluctuate more than the indoor SET*. Since the outdoor air temperature was higher, consequently the outdoor SET* trend was also found higher than the indoor SET* trend. Likewise weather parameters, the indoor SET* trend showed the correspondence with the outdoor SET* trend. The outdoor and indoor SET* values of classroom surrounded by more trees were lower than the classroom surrounded by less tree. Absorbing solar radiation, and evapotranspiration processes trees are capable to lower down the air temperature considerably. In addition, lake can contribute to the reduction of outdoor air temperature compared to the non-lakeside space. Concurrently, the SET* values

near the lake was lower than the non-lakeside space. The high thermal capacity of the lake and evaporation process reduced the air temperature and thereby dropped the SET* values down at the surrounding space of lakeside classroom. In field measurement the lakeside classroom was located on the top floor of a three storied building, which was exposed more to solar radiation. Thereby, in comparing with non-lakeside indoor air temperature and comfort index value slightly different scenario was observed. The overall SET* values indicate the comfort condition in indoor and outdoor are away from the standard comfort zone. Therefore, this is necessary to focus on air temperature reduction and air velocity augmentation to achieve desirable thermal environment.

For model calibration and parametric study, simulation software EnergyPlus 8.7 was used. Air temperature and mean radiant temperature were used for results comparison in the process of calibration. Initially, building specifications and weather data developed by the Solar and Wind Energy Resource Assessment (SWERA) project was inputted in EnergyPlus. The results indicated the correspondence between the simulation results and the measurement results. Then simulation was run through original EnergyPlus weather data (Original epw), configured weather data from tree (Tree epw) and lake (Lake epw) cases to examine the effects of outdoor environmental settings on indoor thermal environment.

The exterior walls affect the indoor thermal environment. Therefore, parametric study was conducted to identify the best composition of materials and construction pattern of exterior wall. In the base case, the exterior wall was composed of plaster, brick, and plaster. Results of parametric study indicated that using concrete instead of brick could lower the air temperature. Depending on layer thickness, concrete can reduce air temperature up to 0.4^{o}C.

To examine the influence of outdoor environmental settings on indoor environment, simulation was run through original EnergyPlus weather data (Original epw), configured weather data from tree (Tree epw) and lake (Lake epw) cases. The influence of tree and lake on the indoor thermal environment were identified. If the effects of trees can be incorporated in outdoor weather condition, the indoor air temperature can be reduced more (up to 1.0^{o}C) compared to the original weather conditions when daytime ventilation schedule was in operation. Further, by introducing the effects of lakes the indoor air temperature can be reduced up to 0.7^{o}C compared to the original weather condition. The air temperature slightly decreases with the increase of ventilation rate in all conditions. The nighttime ventilation slightly decreases the air temperature compared to daytime ventilation.

Finally, the combined impacts of design modification, outdoor environmental settings, and ventilation schedule were examined. Using concrete instead of brick in the construction of exterior wall (as defined in Material 7) along with incorporating tree's influence in outdoor setting can reduce the indoor SET* up to 1.5^{o}C. Moreover, outdoor setting incorporating the influence of lake with same design modification (using Material 7) can lowered the indoor SET* up to 1.1^{o}C. The nighttime ventilation schedule has marginal impact on the SET* reduction and this is also very difficult to operate nighttime ventilation in educational buildings. The presence of trees and lakes in the outdoor space can improve the outdoor and indoor thermal environment. Therefore, integration of design modification, incorporating trees and lakes in outdoor environmental setting, and natural ventilation exhibit better performance in enhancing indoor thermal environment and comfort in university spaces.

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Chapter 1

Introduction

The study background has been described in this chapter along with the purpose and the major objectives of this study. Moreover, the urgence of conducting this study is presented in the rationale of the study section.

1.1 Background of Study

Over the last century, the world is becoming predominantly urban (UN-Habitat, 2013). Increasing urbanization rates are associated with land use and land cover changes, air pollution, and a higher demand for energy consumption (Puliafito, Bochaca, Allende and Fernandez, 2013). Considering the rapid growth of urban population, the global built-up area is also expected to be increased proportionately (World Bank, 2010). The low reflectivity of the urban surface combined with a high density of construction results in an accumulation of heat in the urban environment. This causes a higher temperature that consequently increases discomfort (Taleghani, 2014).

Thermal comfort is one of the vital environmental factors for building occupants to work productively and live well (Hamzah, Gou, Mulyadi, and Amin, 2018, Gou, Lau, and Chen, 2012). A comfortable thermal environment makes people healthy both physically and psychologically. An environment that makes occupants feel too cold or too hot could cause a decrease in work efficiency (Mendell, and Heath, 2005, Wargocki, and Wyon, 2007). Educational buildings are primarily designed to provide a sensible environment to promote teaching and learning (Zomorodian, Tahsildoost, and Hafezi, 2016, and Singh, Ooka, and Rijal, 2018). Activities related to teaching and learning are affected directly by the thermal environment (Mendell, and Heath 2005). Unsatisfactory thermal environment in classroom can result undesirable conditions for both teachers and students. Thermal discomfort can negatively affect the students' learning capacity, performance and health. Hence this is always critical to provide comfort condition in classroom (James, and Christian, 2012).

Demographic and economic changes catalyze the demand for university education in Bangladesh dramatically over the past two decades. Consequently, enrollment in universities has been growing rapidly from 1.7 million in 2010 to 4.1 million in 2018 (UGC, 2019, and

World Bank, 2019). Figure 1.1 presents the recent trend of students' enrollments in the public universities in Bangladesh.

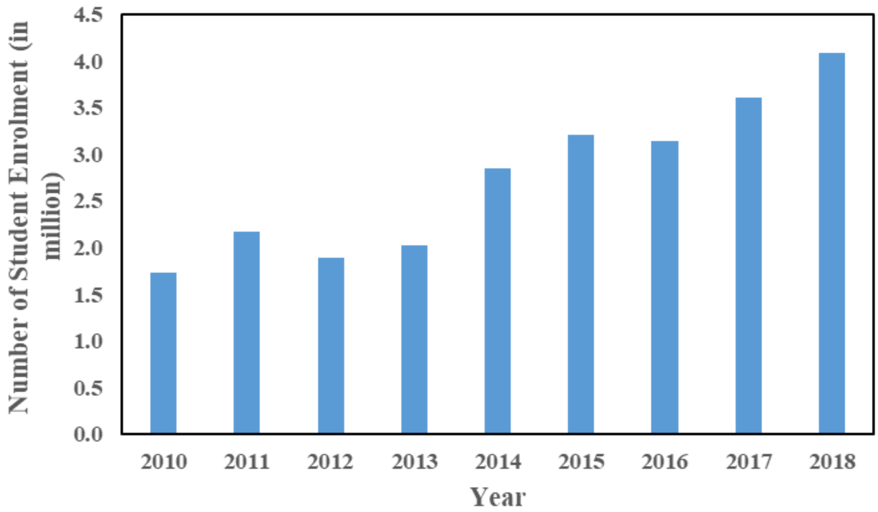


Figure 1.1 University Students' Enrolment Trend in Bangladesh (UGC, 2019)

Consequently, the number of universities also has increased from 82 to 143 during the same period. Figure 1.2 illustrates the growing pattern of tertiary educational institutes of Bangladesh.

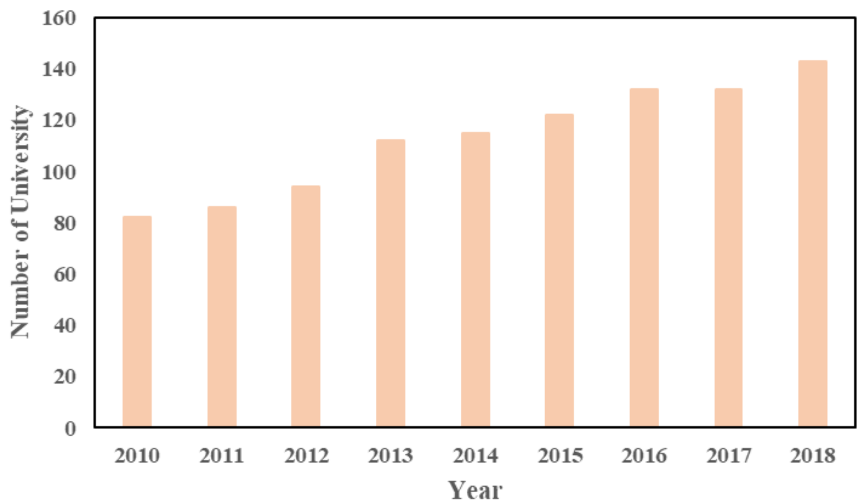


Figure 1.2 Growth of Tertiary Educational Institution in Bangladesh (UGC, 2019)

In addition, the number of teachers has been increased from 15029 in 2015 to 18733 in 2019 (UGC, 2019). Figure 1.3 depicts the number of teachers involved in tertiary education. It is predicted that the demand for tertiary education will continue to grow as the share of youth population with increases from 11 percent in 2010 to 20 percent in 2035 (World Bank, 2019).

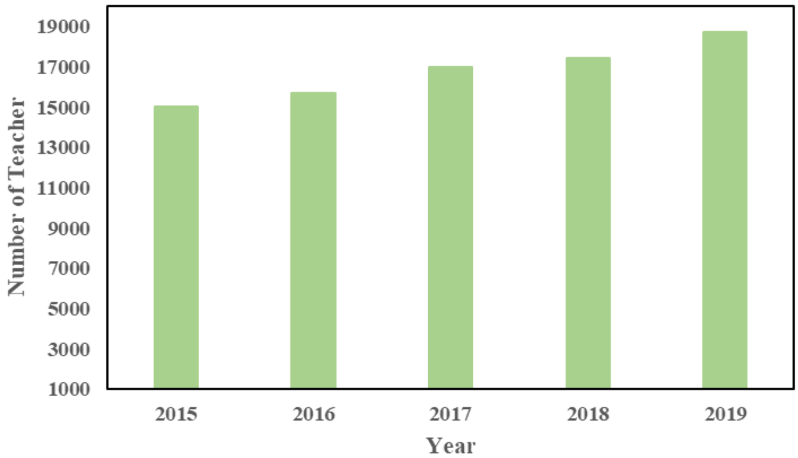


Figure 1.3 Faculty Member Trend in Bangladesh (UGC, 2019)

Moreover, different educational stage and curricula demands different learning approaches and different activities requires desirable classroom environment (Singh, et al. 2019). To attain maximum performance from this large numbers of students and faculty members, promoting thermal comfort in classrooms is inevitable.

Dhaka is a fast-growing mega city in the world located at 23.24°N, 90.23°E and 8.8 m a.s.l. About 13 million people live in the metropolitan area (Kakon, Nobuo, Kojima, & Yoko, 2010). The monthly temperature and relative humidity of Dhaka are presented in Figure 1.4.

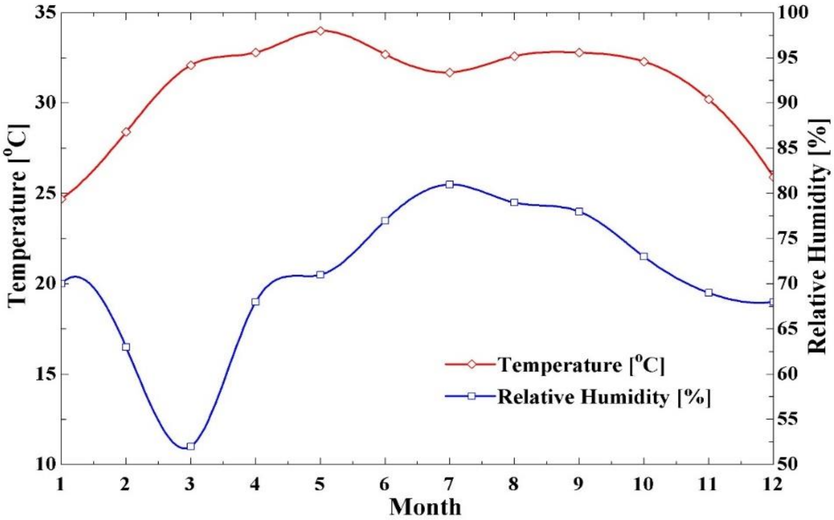


Figure 1.4 Monthly Temperature and Relative Humidity in Dhaka, Bangladesh (BBS, 2015)

The temperature and relative humidity are found higher in most of the months of the year. January and December are the coolest months with temperature of 24.7^{o}C, and 25.9^{o}C, respectively. The temperature tends to increase from the month of March with temperature of 32.1^{o}C. May is the hottest month of the year with temperature of 34^{o}C and relative humidity of 71%. The highest relative humidity (81%) was found in July with a temperature of 31.7 Besides, Dhaka experienced an annual rainfall of 144mm. This higher temperature and relative humidity cause discomfort. Thus, it is necessary to examine the thermal environment and comfort condition in the university spaces to improve the comfort condition. This study, therefore, is an endeavor to investigate the thermal environment and comfort of university spaces in Bangladesh.

1.2 Rationale of Study

The demand for higher education opportunities in Bangladesh has increased dramatically over the past two decades which resulted in a significant expansion of the tertiary education system in the country since 1990s. It is predicted that the demand for tertiary education will increases 20 percent by 2035 (World Bank, 2019). Therefore, the number of universities will also continue to increase (Figure 1.2). Other than home, students spend more time at their educational institutes (Zomorodian, Tahsildoost, and Hafezi, 2016). Since thermal comfort determine the health and productivity of the students, more attention is paid on keeping desirable thermal environment and comfort which augments energy demand for cooling purpose (Prakash & Ravikumar, 2015; Taleghani, 2014).

In Bangladesh, due to rapid population growth, industrialization, expansion in grid connection and increase in the use of electrical appliances energy demand is growing at over 10% per year. Figure 1.5 shows the major energy sources of Bangladesh. This is observed that the energy supply is largely dependent on natural gas (over 72 percent).

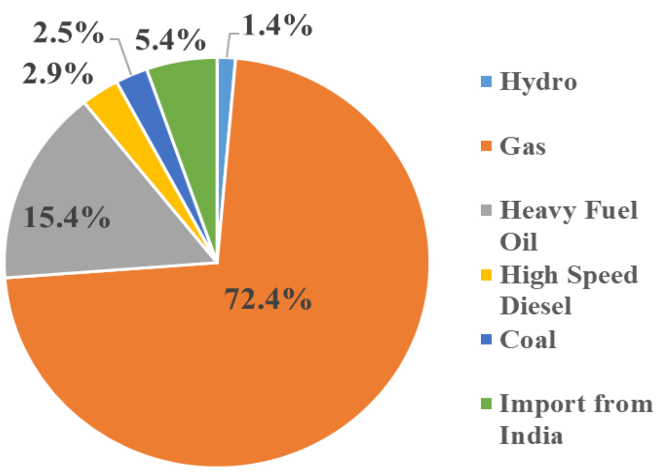


Figure 1.5 Major Energy Sources in Bangladesh (SREDA & Power Division, 2015)

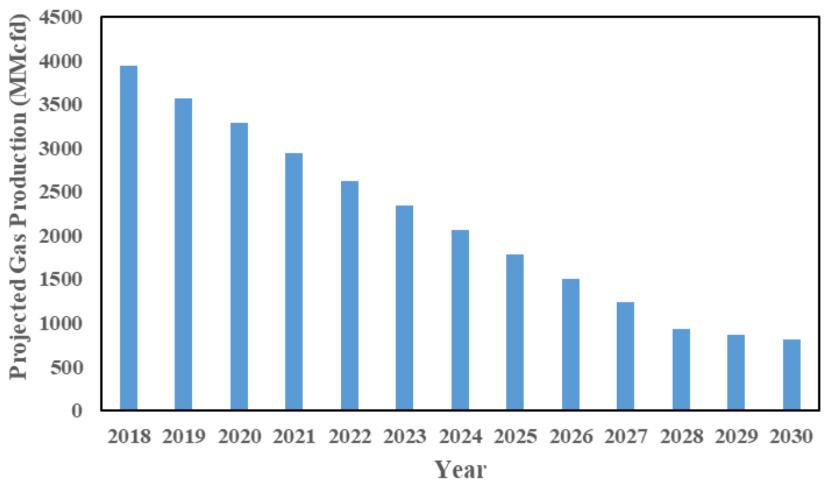


Figure 1.6 Projected Gas Production in Bangladesh (GoB, 2012)

It is anticipated that the gas supply will reach its peak in 2018 and gradually decrease thereafter as proven reserve of gas is depleting progressively (SREDA & Power Division, 2015; Ministry of Finance, 2011). Figure 1.6 shows the projected gas production in Bangladesh. In response to the gradual decrease in reserve, the production of gas tends to decrease in near future (GoB, 2012). In these circumstances, designing the university spaces considering thermal comfort as well as energy implication is critical.

1.3 Objectives of Study

The purpose of this study is to ensure a comfortable and desirable environment in university spaces. To fulfil this purpose some specific objectives have been formulated. The major objectives of this study are mentioned as follows.

- To improve the comfort condition of the university classroom. The status of current comfort condition can be assessed through the comparison with standard comfort and scope of improvement can be identified.
- Trees and lakes have regulating effects on outdoor thermal environment. To examine the effects of outdoor environmental settings such as the cooling effects of ‘Tree’ and ‘Lake’, and ventilation schedule on the indoor thermal comfort for adopting outdoor environmental effects inclusive suitable measures for the improvement of indoor comfort.
- To propose some design considerations for enhancing the thermal comfort of the educational spaces.

1.4 Contribution of This Study

This study is an attempt to examine thermal environment and comfort in indoor and outdoor spaces of university. Taking Jahangirnagar University, Dhaka, Bangladesh, as an example, this study will investigate whether the outdoor environment especially tree and lake have any influence on the indoor environment and if so, the extent of influence will be identified. Moreover, ventilation schedule, and design modification options will also be examined to enhance the indoor thermal environment. Finally, integrated proposals of design modification, ventilation schedule, and incorporating the influences of different outdoor environmental settings in enhancing indoor thermal environment will be presented. These proposals can be useful as an initial guideline for the city planners, designers, and architects to enhance thermal environment and comfort in university spaces.

1.5 Thesis Outline

To improve the thermal environment and comfort condition on university spaces considering the cooling effects of tree and lake, along with building design considerations this manuscript comprises seven chapters. The dissertation outline is described as follows. Figure 1.7 illustrates structure of the dissertation.

As an introductory chapter, **Chapter 1** states the background of the study, research objectives, research contribution, and the rationale of studying thermal environment and comfort in tropical university spaces.

Chapter 2 presents the findings of the previous studies conducted on the thermal environment and comfort in educational buildings. Besides, results of thermal environment studies near green are, and water features have been accumulated along with studies relating the thermal environment and building characteristics, and policies related to the building construction in Bangladesh. After reviewing the above-mentioned literature critically, an attempt has been made to identify the rationale of conducting the current study.

In **Chapter 3**, profile of the study sites, protocol of device set up, schedule of weather data measurement, and procedure of comfort index calculation have been described. Furthermore, the process of simulation study to examine the cooling effects of tree and lake on indoor thermal environment has been narrated here.

Depending on outdoor environmental settings and building characteristics, evaluation of thermal environment and comfort have been done in different cases such as classroom surrounded by more tree and less tree, lakeside classroom and non-lakeside classroom. Case wise illustrations of the thermal environment are included in **Chapter 4**.

Chapter 5 depicts the thermal comfort conditions in different cases. Thermal comfort conditions in different cases have been evaluated by the comfort index named as Standard Effective Temperature (SET*).

In **Chapter 6** the model calibration procedure and weather data validation are presented to examine the effect of outdoor environmental settings on the indoor thermal environment. Then the cooling effects of tree and lake on indoor thermal environment has been investigated by calibrated model coupled with incorporation a parametric study. Findings from investigating the cooling effects of tree and lake on indoor thermal environment, and parametric study, ways will be compared to improve the current condition.

Chapter 7 accumulates the key findings from the field measurement results and simulation results to evaluate the effect of outdoor environmental settings on indoor thermal environment. Proposed design considerations based on findings to attain desirable environment in university spaces are also presented in this chapter.

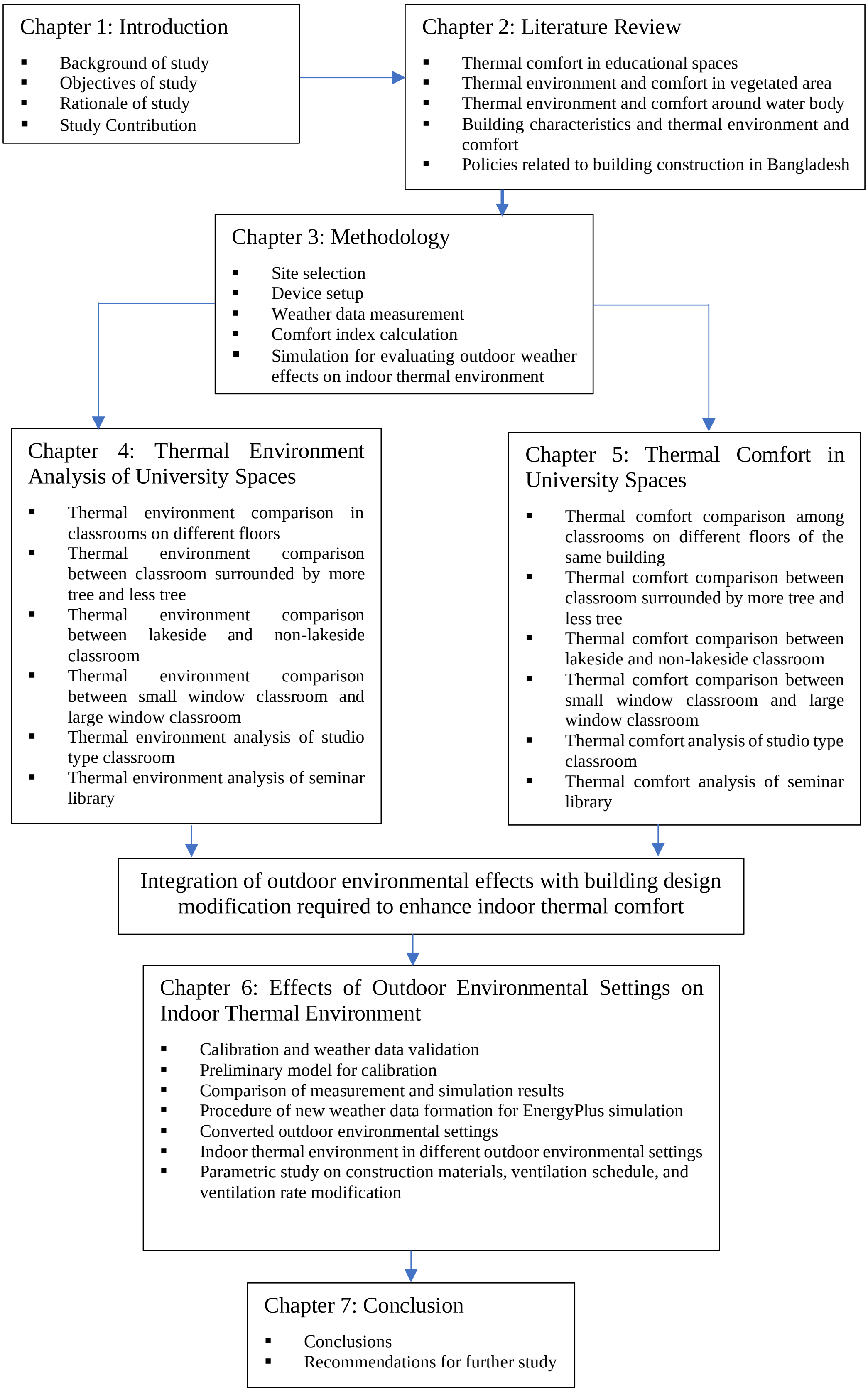


Figure 1.7 Flowchart of Dissertation Structure

1.6 Conclusion

Thermal environment and comfort have a notable effect on human health and productivity. Teaching and learning related activities are influenced by the thermal environment. Thermal discomfort can negatively affect the students and teachers' health, productivity, and performance. Hence, this study evaluating the thermal environment and comfort in university spaces, attempts to propose design considerations incorporating the effects of tree and lake in outdoor space along with ventilation schedule to enhance the comfort condition.

Chapter 2

Literature Review

This chapter presents the findings of the previous studies conducted on the thermal environment and comfort in educational buildings. Besides, results of thermal environment studies near forest, park, lake, river, and water features have been accumulated. Furthermore, studies relating the thermal environment and building characteristics are summarized. Finally, policies related to the building construction in Bangladesh has been reviewed. After reviewing the above-mentioned literature critically, an attempt has been made to identify the rationale of conducting the current study.

2.1 Thermal Comfort in Educational Spaces

The significance of the thermal environment and comfort cannot be undermined, especially in educational infrastructures (Barbhuiya, and Barbhuiya, 2013). The unsatisfactory thermal environment in the classroom can result in undesirable conditions for both teachers and students and can adversely affect their performance and productivity (James, and Christian, 2012). Uline and Tschannen-Moran, (2008) examined the influence of indoor thermal environment on student achievement. They found the quality of a school environment and student achievement in English and mathematics possessed a fairly strong association.

Wong and Khoo (2001) conducted a study in mechanically ventilated classrooms in Singapore to assess thermal comfort. Objective measurement showed that none of the classrooms had thermal conditions falling within the comfort zone of ASHRAE standard 55. The study found the acceptable temperature lies between 27.1ºC to 29.3ºC and 28.8ºC as neutral temperature. Ismail, et al. (2010) carried out their study in a computer laboratory and found PMV values exceeding the comfort level initially. However, comfortable thermal environment was attained by operating air conditioner consistently. A small-scale study was conducted by Pellegrino, Simonetti, and Fournier (2012) in two university classrooms ventilated by fans in Kolkata, India. Calculated PMV values indicated the thermal conditions of the classrooms are away from the comfort zone. Lee, Mui, Cheung, and Wong (2012) carried out a thermal comfort study in air-conditioned university classrooms of Hong Kong and Taiwan. Majority of the students were satisfied with the thermal environment in both countries. Kamaruzzaman and Tazilan (2013) assessed thermal comfort of school classroom in Malaysia. Field measurement data showed that most classrooms do not provide a thermal comfort environment and satisfaction for teachers and students. PMV values were far beyond of comfort range. This study determined 26.5ºC as the maximum acceptable temperature. Mishra and Ramgopal (2014) conducted thermal comfort study in undergraduate laboratories in India. They estimated the maximum PMV value of 3.1 and find a comfort range of 20-31ºC. Baruah, Singh and Mahapatra (2014) investigated thermal comfort in naturally ventilated university classroom in Assam, India during end of winter and beginning of summer. Their assessment revealed that comfort temperature ranges from 22ºC to 23.5 °C in winter month and 27.3ºC to 30.7 °C in summer month. Rajkumar, Amirtham and Horrison (2015), assessed thermal comfort of university studio classrooms in Tamil Nadu, India. Objective measurement was carried out to measure air temperature and relative humidity. Air temperature tends to increase as time progresses in the measurement days and in corresponds relative humidity decreases. Ali, Matrinson and Almaiyah (2017) evaluated indoor environmental performance of laboratories in Nigerian university. The PMV values of two laboratories were found 1.43, and 0.79, respectively. However, these values did not comply with actual mean vote results. Hence, they suggest further investigation.

Rangsiraksa (2006) conducted a thermal comfort study on the university students and staffs as subjects in naturally ventilated buildings in Bangkok, Thailand. This study identified the comfort temperature as 28ºC in natural ventilated buildings in summer season. Puteh et al., (2012) carried out a study in naturally ventilated buildings located in warm and humid climates, Malaysia to identify the students' perceptions towards classroom thermal comfort. The survey results stated that 45.5% of the students feel that their classroom is hot and 48.3% said that they are not satisfied with the heat of their classroom. Students also mentioned that their health were affected by the classroom's thermal condition. Liang, Lin, and Hwang (2012) conducted a study in naturally ventilated classrooms in primary and secondary schools in Taiwan. They identified 29.2ºC as a neutral temperature, and the outdoor air temperature was associated the neutral temperature. Dhaka et al., (2013) made a study in naturally ventilated hostel buildings was carried out in the summer season of Jaipur city lies in composite climate zone of India. Through regression analysis, with an average clothing of 0.4 Clo, the neutral temperature was found to be 30.2°C. Moreover, acceptable air velocity and relative humidity were found to be 0.5 ms^{-1} and 36%, respectively. A thermal comfort study was conducted by Yun et al., (2014) for the kindergarten children in naturally ventilated classrooms in Seoul, Korea. They found that children were more sensitive to changes in their metabolism than adults, and their preferred temperature was lower than that predicted by the PMV model. They suggested developing a new PMV model for children considering thermal sensation factor. Subhashinia and

Thirumaran (2018) assessed thermal comfort in naturally ventilated architecture building, India. Estimated PMV value indicated thermal discomfort of the occupants. They suggested to use shading devices for enhancing thermal comfort. Costa, Freire, and Kiperstok (2019) investigated the efficiency of natural ventilation through the windows and other openings in the faculty room and classrooms at the Federal University of Bahia, located in the city of Salvador, Brazil. They revealed that poor maintenance of building's windows and window frames compromised their ability to facilitate efficient natural ventilation and significantly reducing the capacity for thermal regulation in the building. Rahman and Tuhin (2019) evaluated impact of daylight on learning environment in a school, Ishwardi, Bangladesh. They, however, focused on assessing visual comfort evolved from the penetration of daylighting with different placement of window.

2.2 Thermal Environment and Comfort in Different Environmental Settings

Previously several studies were conducted on the thermal environment and comfort in different environmental settings like near forest, park or other green spaces, river, lake, other water feature e.g., fountain. Major findings of some of these studies will be summarized in the following sections.

2.2.1 Thermal Environment and Comfort in Vegetated Area

Providing solar protection through shading, absorbing solar radiation, affecting air movement, and evapotranspiration processes trees are capable to lower down the air temperature considerably. Thus, trees and green spaces in the form of parks in urban area have significant contribution in the improvement of microclimate and provision of thermal comfort (Cohen, Potchter, & Matzarakis, 2013; Lin, Tsai, Hwang, & Matzarakis, 2012; Müller, Kuttler, & Barlag, 2013). Bowler et al. (2010) compared the air temperature in parks of different sizes ranging between 0.1 and 120 ha. They found on average a park is 0.9°C cooler during the daytime. Additionally, they claimed air temperature could be lower in larger parks and parks with trees. Mahmoud (2011) carried out a study on microclimate and human comfort in an urban park, Cairo, Egypt. He identified the canopy shading can lower the radiative fluxes under trees. Thereby, the outdoor thermal comfort condition under trees found better compared to the spaces exposed to the direct sunshine in greater extent.

Ng, Chen, Wang, and Yuan (2012) studied the cooling effect of green space in a high-density living environment, Hong Kong. They found trees were more effective in cooling pedestrian areas rather than roof greening and suggested to plant trees nearer to the places where human activities are concentrated. Buyadi, Mohd and Misni (2013) investigated the effects of vegetation on Land Surface Temperature (LST) using satellite image data in Shah Alam City, Malaysia. Their results indicated that a decrease in vegetation increase the LST of an area.

Skoulika, Santamouris, Kolokotsa, and Boemi (2014), examined the cooling effect of an urban park in Athens, Greece. They found the average air temperature in the park lower than surrounding reference urban stations during daytime. Lu et al. (2017) inspected the cooling effect of an urban forest park located in a dense city center area Chongqing, China possessed a hot and humid climate. They found the air temperature about 0.8^{o}C lower inside park. Park et al. (2017) conducted a study in Seoul, South Korea and found small green spaces (300 m^2) can result in 1^{o}C air temperature reduction. They also identified that up to 2^{o}C air temperature can be reduced by relatively larger parks with an area of 650 m^2.

Sun and Chen (2017) studied green space dynamics and land surface temperature (LST) in the Beijing, China. They emphasize on preserving natural forest for climate mitigation in greater extent. Ruiz, Sosa, Correa, and Cantón (2017) conducted field measurement in a non-forested urban canyon and in 18 representatives of forested ones in Mendoza, Argentina. They concluded that comfort condition can be enhanced up to 60% by urban forest. Anjos and Lopes conducted a study on park's cooling effect on urban heat island in Aracaju, North-Eastern Brazil. They concluded that urban park could cool the air temperature 1.5^{o}C. Aram, García, Solgi, Mansournia, (2019) argued that urban green spaces promote thermal comfort for the citizens by reducing urban heat island effect. Their study revealed that urban green space can reduce the temperature up to 1.5^{o}C. Nasrollahi, Ghosouri, Khodakarami, and Taleghani (2020), made an extensive review on the heat mitigation approaches in urban environment. They claimed trees exploiting their shading effects to be the best heat mitigation strategy for the enhancement of thermal comfort at pedestrian level.

2.2.2 Thermal Environment and Comfort around Water Body

Triyuly, Triyadi, and Wonorahardjo (2020) claimed that air temperature could be reduced during the daytime by exploiting the water body's properties of air-cooling effect and delay in re-emission of heat energy. Wu, Wang, Fan, and Xia (2018) showed that reservoir, lake, and green space have direct impacts on the urban thermal environment. Employing its transparency, high thermal capacity, and evaporation process the water bodies act as an efficient heat sink and reduce the air temperature (Syafii et al. December 2017). These unique characteristics of water bodies attract city planners and architects around the globe to incorporate water bodies in their designs to regulate urban thermal environments (Shafaghat et al., 2016). Jusuf, Wong, and Syafii (2009) carried out a study in Singapore and found air temperatures cooler up to 1.8°C near the water features compared to surrounding built areas during clear sunny days. Guo-yu et al. (2013) stated that water bodies in urban areas significantly affect the urban climate and mitigate the Urban Heat Island (UHI) effect due to the thermal properties of water and evaporation. They identified a water body with a surface area of 16 m^2 that could cool by 1°C up to 2826 m^3 of surrounding space. Syafii et al. (2017) found that the thermal environment inside an urban canyon with a pond is better than that without a pond, particularly during the daytime. Jin, Shao, and Zhang (2017) mentioned that being one of the constituent elements of the underlying surface, the water body plays a regulating effect on the microclimate of residential districts, especially in summer. Their results suggest that both centralized and scattered water bodies can improve the microclimate of the residential district. Mohammad S. Albdour and Balint Baranyai (2019) conducted a study to measure the effect of water features on the microclimate in Pecs, Hungary. Their results showed that water elements played a role in reducing air temperature and mean radiant temperature, while a slight effect on Predicted Mean Vote (PMV). Hathway and Sharples (2012) examined the cooling effect of a water body in the Sheffield, United Kingdom. Their result showed that water body could decrease temperature with an average of 1^oC during summer season. Farajzadeh and Matzarakis (2012) conducted a study on the thermal comfort conditions around a lake in Iran. Analyzing Cooling Power and Physiologically Equivalent Temperature (PET), they identified the suitable periods for tourism and recreation activities. Xi et al. (2012) investigated outdoor thermal environment and comfort around campus clusters in Guangzhou, China. They identified that different outdoor thermal environments resulted from different man-made elements such as pilotis, squares, lawns, and lakes.

2.3 Thermal Environment and Comfort and Building Characteristics

Along with ambient weather conditions, the building characteristics including, layout, orientations, height, properties of construction materials, window sizes, window-to-wall ratio (WWR), shading, and ventilation strategies are considered as key modifiers of the indoor thermal environment and comfort as well as energy consumption (Liping and Hien, 2007, and Tong, Wong, Tan, and Jusuf, 2019). Liping and Hien (2007) investigated the effects of different ventilation strategies and facade designs on indoor thermal environment for naturally ventilated residential buildings in Singapore. They found full day ventilation, north and south-facing facades, and window to wall ratio of 0.24 to be better for the indoor thermal environment. Hassan, Guirguis, Shaalan, and El-Shazly (2007), examined the effects of opening location and size, and building orientation on natural ventilation. They claimed that an increase in the window to wall ratio the indoor thermal comfort can be improved to a greater extent. Besides, the north and south-facing facades could improve the comfort compared with east and west-facing facades. They also found the air flow pattern and ventilation was improved with two openings rather than one opening.

Daghigh (2015) reviewed a number of studies on the thermal comfort, indoor air quality, and ventilation of the offices, classrooms and residential buildings in Malaysia and the surrounding regions. These studies, however, conducted individually on the above-mentioned issues rather than investigate their parameters and their effects on each other concurrently. Considering the significant role of windows on buildings' ventilation, he suggested the further investigation should integrate the ventilation and thermal comfort simultaneously. Tong, Wong, Tan, and Jusuf (2019) carried out a field measurement to examine the effects of façade design parameters on indoor thermal environment in four residential sites, Singapore. They pointed out that façade orientation, window size, and ventilation strategies considerably affect the indoor air temperature.

Watson (1983) mentioned that building envelope is a system that controls heat exchange between the indoor and outdoor environments. The acceptance or rejection of heat gain from the external and internal heat sources is the basic control mechanism which establishing a new microclimate for the indoor environment. The building envelope acts as key interface between the indoor and outdoor environment mainly comprises of foundation, wall, fenestration, roof, shading device. Among these, walls are the key elements in building envelop system which affect the thermal performance of a building (Sadineni, Madala, and Boehm, 2011).

Givoni (1976) stated that the heat exchange rate and direction through the building envelope depend on several parameters like the solar gain, indoor temperature, outdoor temperature, material thermophysical properties, and exposed surface area. Heat transfer through the building wall is complex and dynamic process which occurs by the conduction, convection, and radiation. In the daytime, the solar radiation hits the external wall surface. A part of this solar radiation is absorbed and conducted across the material and the other part is released to the outdoor environment. The interior surface of the wall then exchanges heat with the room air and other surfaces through the convection and radiation. The indoor air temperature is regulated by these heat transfer methods and consequently influences the state of thermal comfort.

2.4 Building Construction Related Polices in Bangladesh

In Bangladesh, there are two major policies to guide the building construction titled as "Dhaka Megacity Building Construction Rules 2008" and "Bangladesh National Building Code 2015".

Firstly, The Dhaka Building Construction Rules 2008 prescribed the building permission approval procedure, Floor Area Ratio (FAR), Setback rules, Maximum Ground Coverage (MGC) for building construction. Secondly, Bangladesh National Building Code 2015 dealt with a range of development areas including construction, structure, material, geo-technical and seismic aspects, fire protection, disaster responsive issues. These policies are concerned more on the site density, building safety, and disaster related issues and the thermal environment and comfort issues are not addressed adequately.

2.5 Conclusion

Thermal environment and comfort have notable impact on human health, performance, and productivity. Thermal environment in educational buildings is more important because it affect the teaching and learning related activities. As a result, several studies were conducted on the thermal environment and comfort around the world. Previous studies focused on the importance of thermal environment and comfort in educational building along with relation between classrooms' environment and students' performance. Majority of the studies attempted to determine a neutral temperature and a range of comfort temperature. Some studies mentioned about the usage of shading devices and maintenance of windows to regulated thermal environment. The presence of green spaces and water bodies like lake in the outdoor area have considerable effect on outdoor as well as indoor thermal environment. Most of the previous studies on urban thermal environment and urban heat island mitigation were focused on the regulating effects of green area and water features in outdoor spaces with a very marginal focus on the effects of outdoor environmental settings on indoor thermal environment, especially the cooling effects of trees and lakes simultaneously in educational spaces. Thus, this is important to integrate the effects of outdoor environmental setting in analyzing indoor thermal environment and comfort.

Thermal environment and comfort study in educational buildings are rare in Bangladesh. One study was found on the visual comfort in school building has been evaluated considering various placement of windows. To ensure better performance of the students and teachers, this is imperative to conduct thermal comfort study in educational buildings. Moreover, the policies related to building constructions in Bangladesh did not address the thermal environment and comfort issue adequately. These policies are mainly concerned with building permission approval process, floor area ratio, setback rules, building safety, and disaster related issues. Considering occupants' health and wellbeing as well as energy implication, this is necessary to incorporate the thermal comfort issues in building code and related policies. This study, therefore, is an attempt to evaluate the thermal environment and comfort in university classroom incorporating the outdoor environmental setting along with building design considerations.

Chapter 3

Research Methodology

This chapter will present the entire research methodology. First, a brief overview of the field measurement sites will be described. Second, the weather data measurement devices set up process will be stated in selected sites along with measurement schedule. Third, the process of calculating thermal comfort index will be discussed to evaluate thermal comfort condition in different university spaces. Finally, the process of simulation study for examining the outdoor weather effects in indoor thermal environment will be presented in this chapter.

3.1 Site Selection and Description

This study was conducted in different classrooms and those surrounding areas of Jahangirnagar University, Bangladesh. Geographically it lies between 23°77´ N and 90°38´ E (Figure 3.1 & Figure 3.2). The university comprises an area of about 2.8 km^2 and is located 32 km north of Dhaka city.

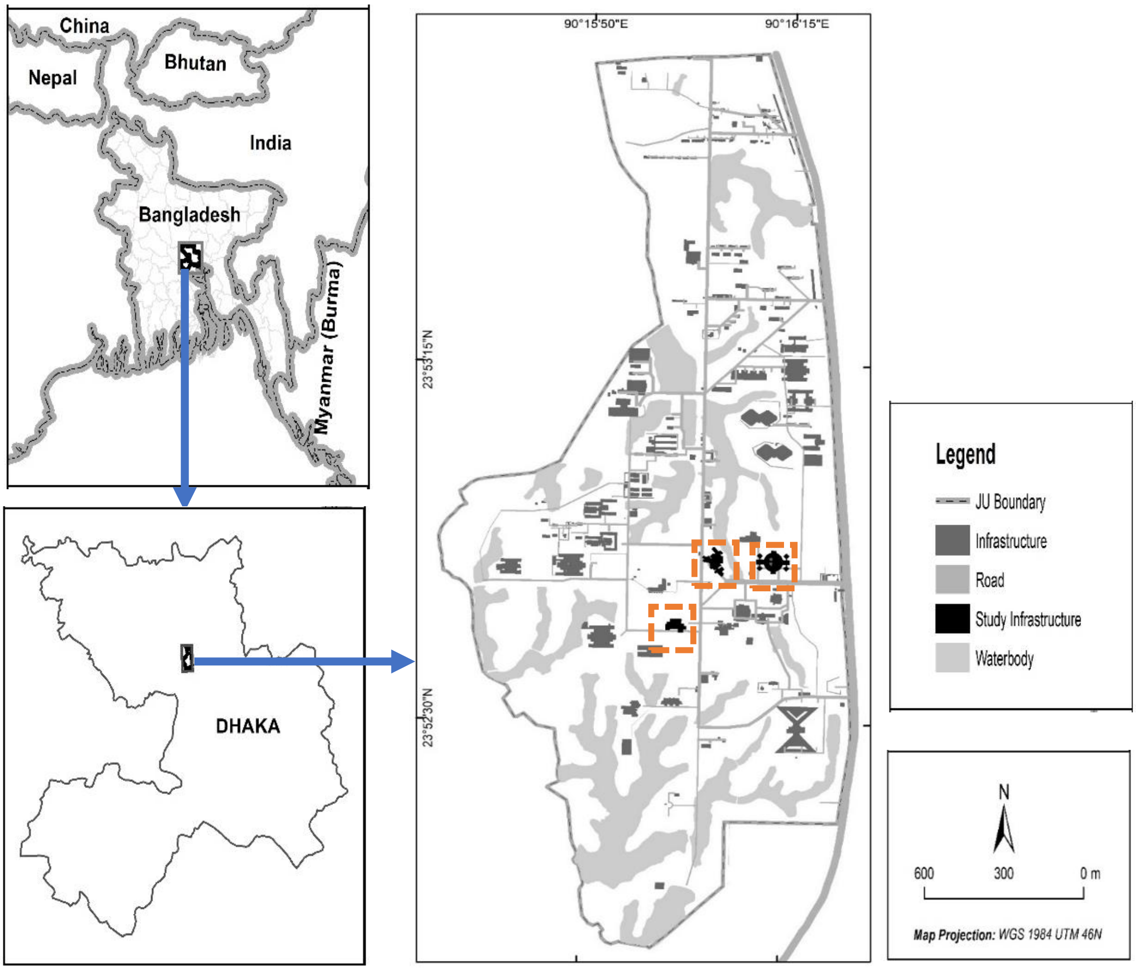
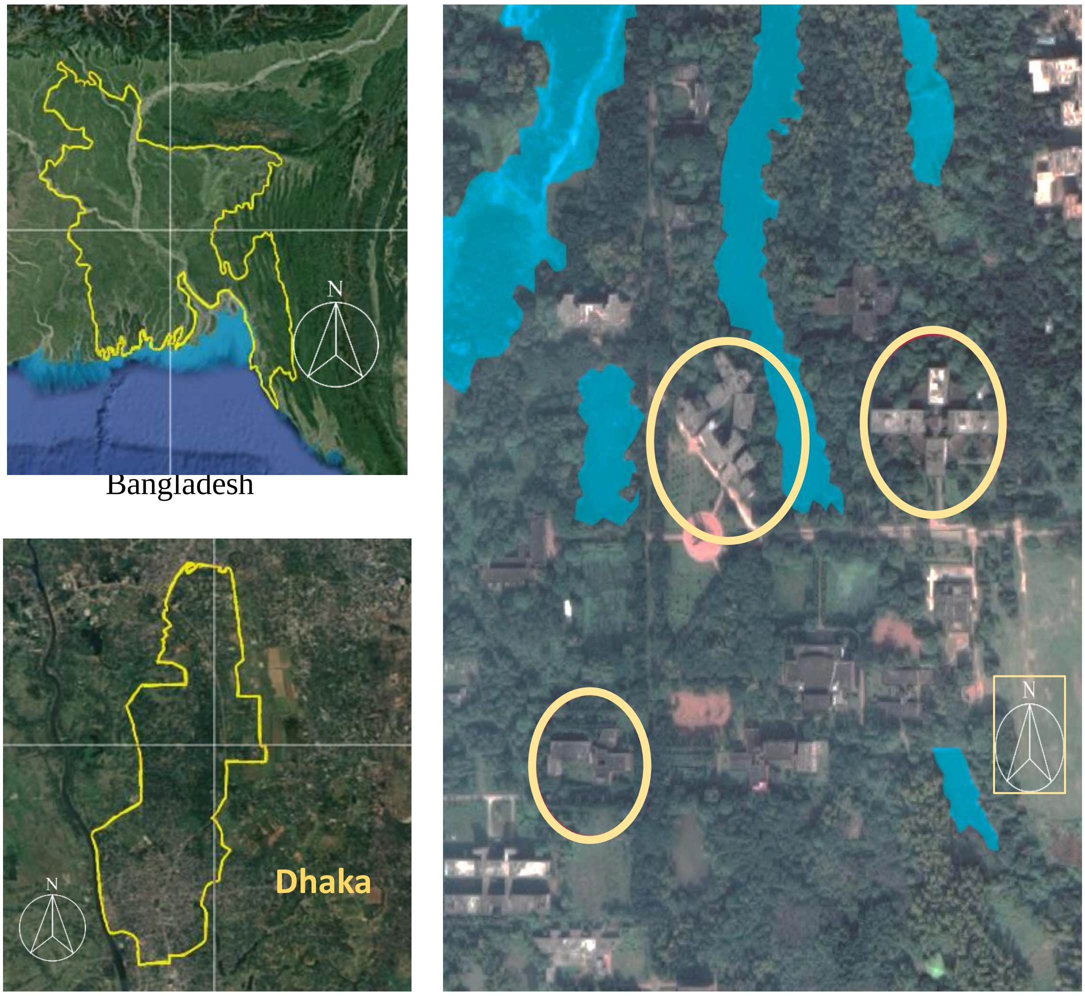


Figure 3.1 Location Map of the Study Area



Jahangirnagar University Location of Target Building

Figure 3.2 Location Image of the Study Area

Here climate can be characterized as hot, rainy, humid summers and dry and cool winter possessing total annual rainfall of about 1,800 mm and 86% mean relative humidity. More temperate months range from April to October (Mondol, Kazi, Rahman, Rakib, 2019; Nahid, 2014 and Nahid, Begum, Feeroz, 2016). The rectangular dotted lines in Figure 3.1 and the yellow circles in Figure 3.2 shows the specific site location of the study area. Figures 3.3-3.5 present some beautiful places of Jahangirnagar University. The following sub-sections presents a brief overview of the sites selected for each case.

Figure 3.3 Monuments, Jahangirnagar University

Figure 3.4 Tree Area, Jahangirnagar University

Figure 3.5 Lake, Jahangirnagar University

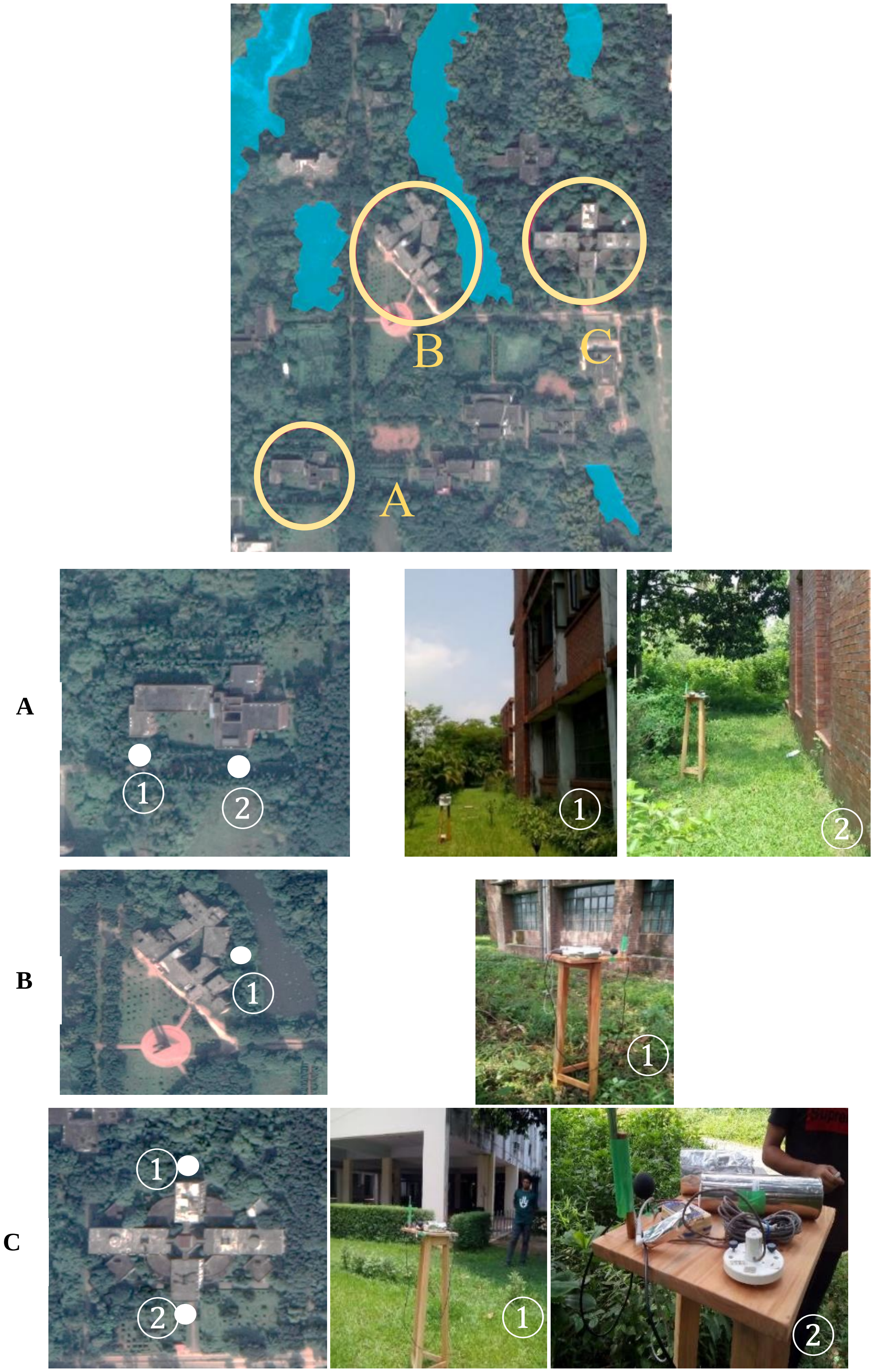


Figure 3.6 Building Locations for Field Measurement

Figure 3.6 shows the building locations for field measurement to collect weather data. Here, A, B, and C indicate the location of buildings and 1, and 2 locate the outdoor weather data measurement points. The following sections will briefly describe the overview of the field measurement sites.

3.1.1 Case 1: Classrooms in Different Floors of the Same Building

For Case 1, three classrooms have been selected in the same building. The classrooms are located on the 1st, 2nd, and 3rd floor of a three-storied building. The key features of the classrooms are presented in Table 3.1. Figures 3.7 shows the building, room location. Figure 3.8-3.11 present the plans and position of measurement devices in the classrooms.

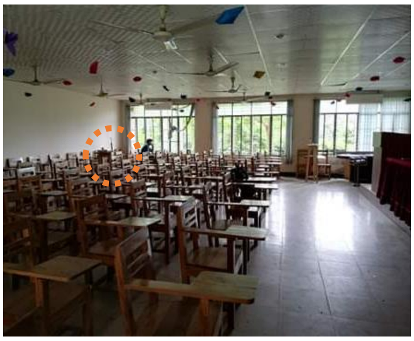
Table 3.1 Major Specifications of Different Floor Classrooms

Parameter	1st Floor Classroom	2nd Floor Classroom	3rd Floor Classroom
Dimensions	12.18m x 9.87m x 3.50m	12.19m x 6.67m x 3.50m	12.19m x 6.67m x 3.50m
Area	120.20 m^2	81.30 m^2	81.30 m^2
Volume	420.70 m^3	284.60 m^3	284.60 m^3
Level	1st floor	2nd floor	3rd floor
Orientation of Window	East, West	East	East
Total Window Area	19.40 m^2	9.40 m^2	9.10 m^2

(a) Building Location

(b) Classroom Location

Figure 3.7 Building and Classrooms Locations in Three Different Floors



(c) First Floor Classroom

(d) Second Floor Classroom

(e) Third Floor Classroom

Figure 3.8 Classrooms Located in Three Different Floors

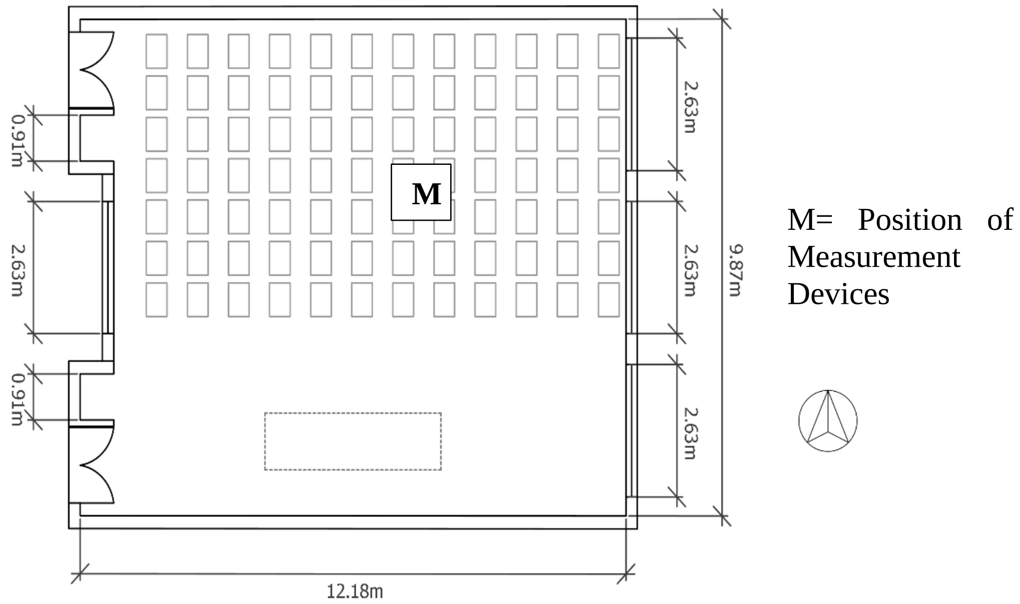


Figure 3.9 Plan of 1st Floor Classroom

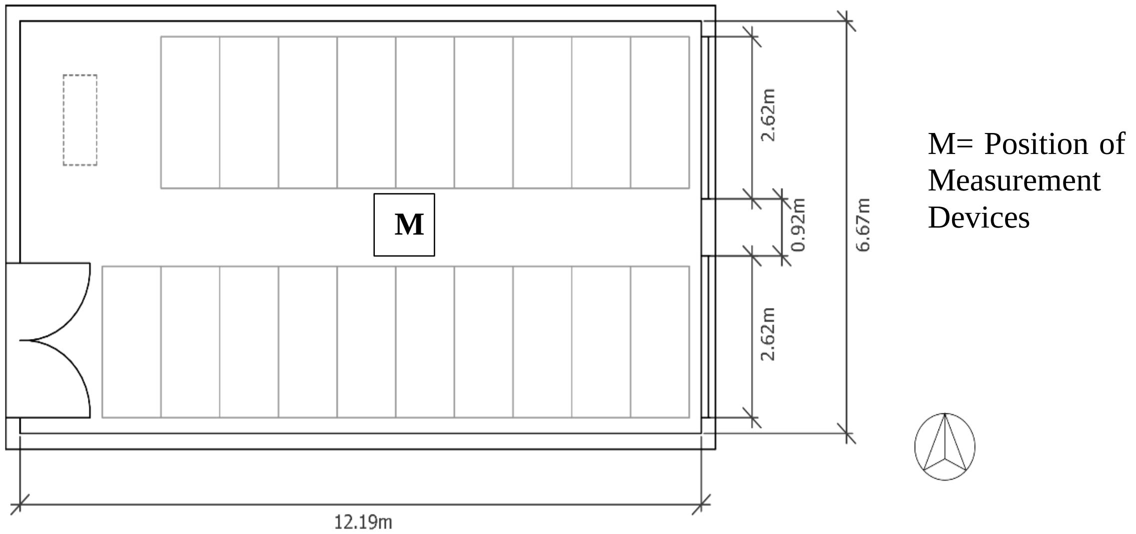


Figure 3.10 Plan of 2nd Floor Classroom

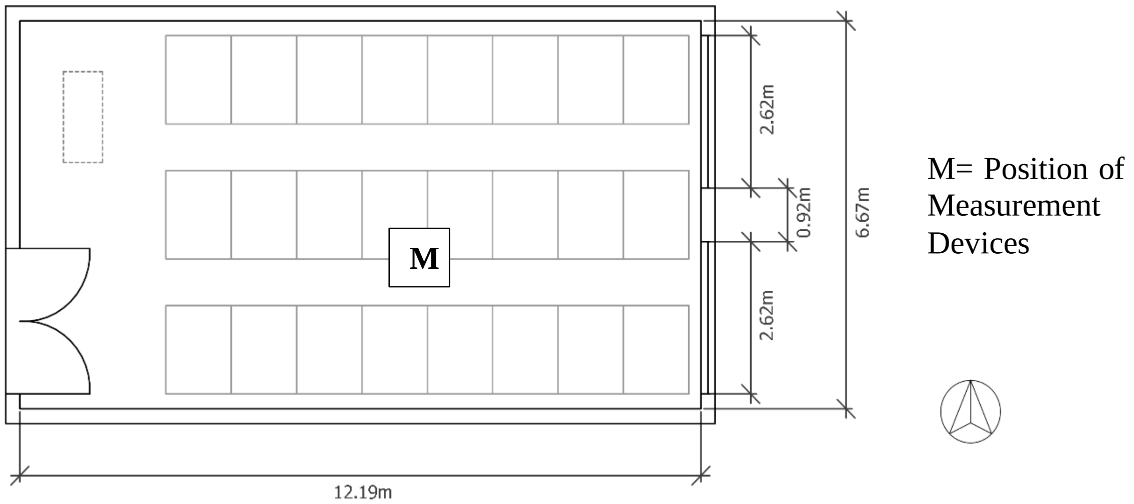


Figure 3.11Plan of 3rd Floor Classroom

The area and volume of the 2nd Floor and 3rd Floor Classroom are same. The 1st Floor Classroom is larger than other two classrooms in area and volume. Besides, the window area of 1st Floor Classroom is also larger than other two classrooms. The 1st floor classroom has window on east and west facing wall. On the other hand, 2nd and 3rd floor classrooms have window only on the east facing wall. East facing walls are the exterior wall for all the classrooms. Ceiling fans are installed in the classrooms.

3.1.2 Case 2: Classrooms Surrounded by More Tree and Less Tree

In Case 2, two different classrooms of one building have been selected (Figure 3.14) for field measurement. Classroom Surrounded by More Tree (1525.3 m^2) is located on the north side of the Social Science Building (Figure 3.14 (b)). In contrast, Classroom Surrounded by Less Tree (307.5 m^2) is located on the south side of the same building (Figure 3.14 (d)). Table 3.2 states the key features of the classrooms. Figures 3.12-3.13 present the plans and position of measurement devices.

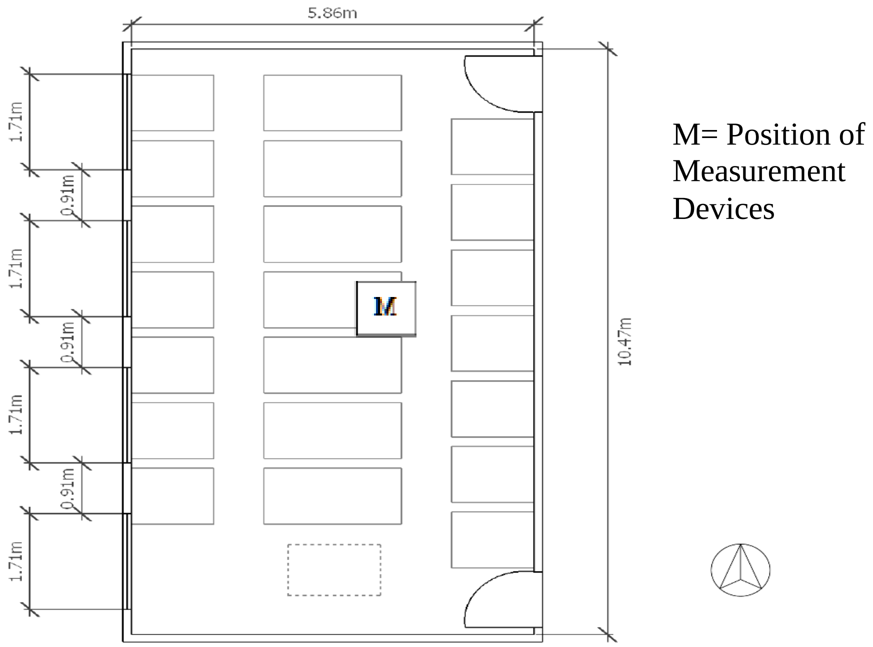


Figure 3.12 Plan of More Tree Classroom

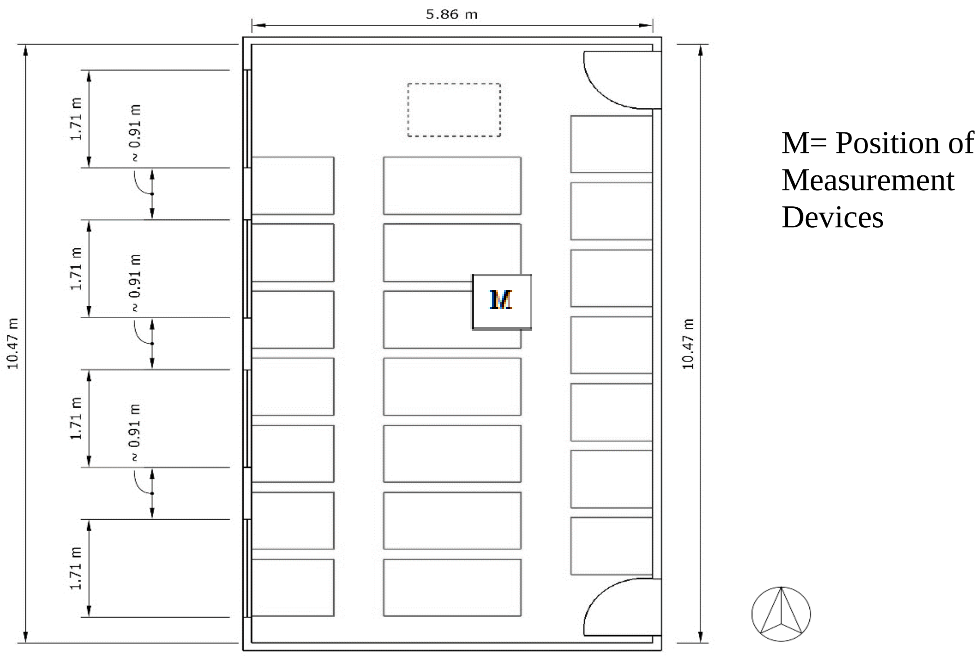
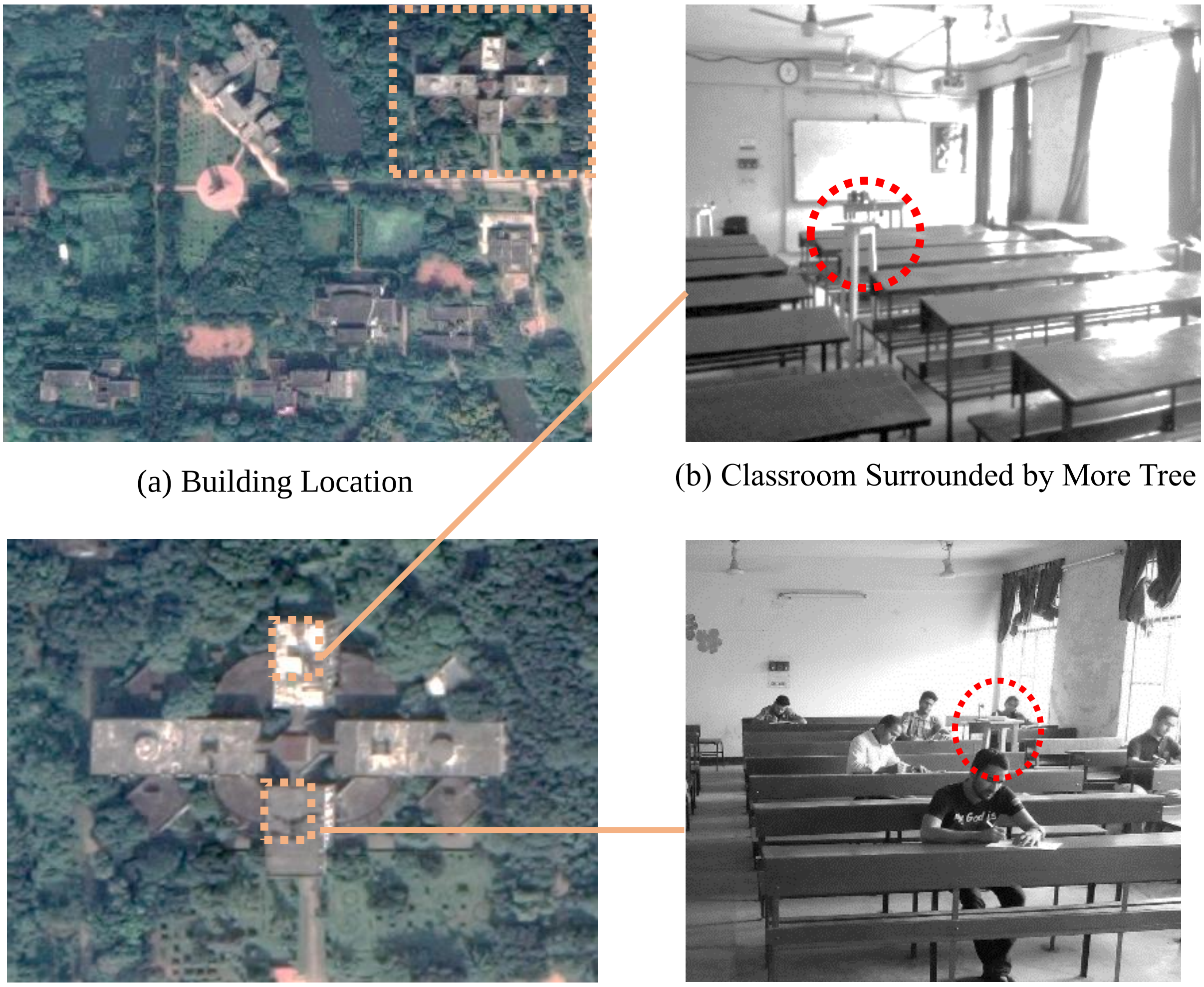


Figure 3.13 Plan of Less Tree Classroom



(a) Building Location

(b) Classroom Surrounded by More Tree

(c) Classroom Location

(d) Classroom Surrounded by Less Tree

Figure 3.14 Classroom Locations and Positions of Measurement Devices for Case 2

Table 3.2 Major Specifications of More Tree and Less Tree Classrooms

Parameter	More Tree Classroom	Less Tree Classroom
Dimensions	10.47m x 5.86 m x 3.20m	10.47m x 5.86m x 3.20m
Area	61.90 m^2	61.90 m^2
Volume	198.20 m^3	198.20 m^3
Level	2^{nd} floor	2^{nd} floor
Orientation of Window	West	West
Window dimensions	1.75 m x 1.95 m	1.70m x 1.95m

Both the classrooms are same in dimension, area, and volume. The windows of the classroom are located on the west facing wall. The window sizes are same for both the classrooms. West facing walls are the exterior wall for the classrooms. Two doors are placed on the east facing walls for each classroom. Ceiling fans are installed in the classrooms.

3.1.3 Case 3: Lakeside Classroom and Non-lakeside Classroom

Lakeside and Non-lakeside Classroom are selected in two different buildings for Case 3. Table 3.3 describe an overview of two classrooms. The building, room location, plans and position of measurement devices are presented in Figures 3.15-3.17.

Table 3.3 Major Specifications of Lakeside and Non-lakeside Classrooms

Parameter	Lakeside Classroom	Non-lakeside Classroom
Dimensions	12.19 m x 6.67 m x 3.50 m	10.47 m x 5.86 m x 3.20 m
Area	81.70 m^2	61.90 m^2
Volume	286.10 m^3	198.20 m^3
Level	2^{nd} floor	2^{nd} floor
Orientation of Window	East	East
Window dimensions (Area)	0.38 m x 1.27 m (9.10m^2)	1.70m x 1.95m (13.30m^2)

(a) Building Locations

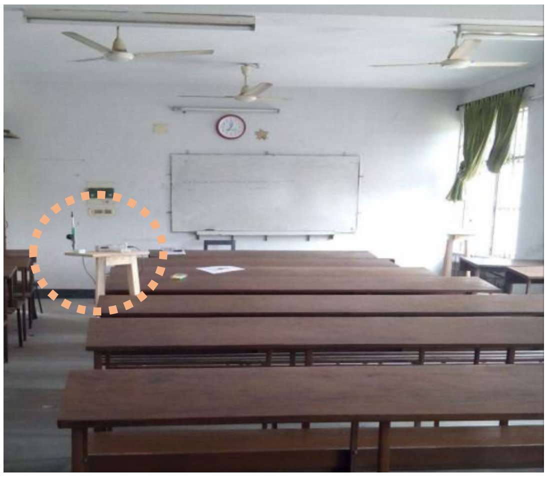
(b) Room Location

(c) Lakeside Classroom

Figure 3.15 Classroom Locations and Positions of Measurement Devices for Case 3

[Continue in Next Page]

(d) Room Location



(e) Non-lakeside Classroom

Figure 3.15 Classroom Locations and Positions of Measurement Devices for Case 3

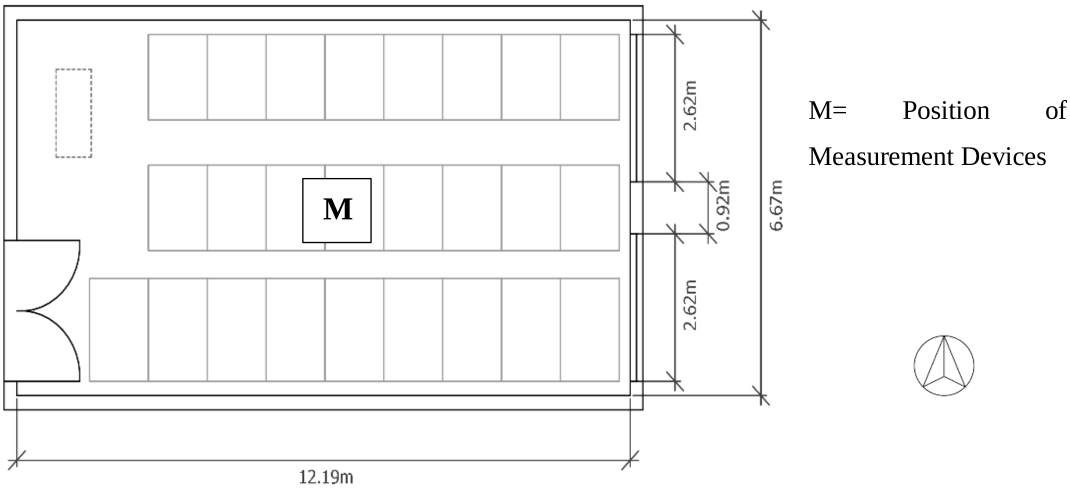


Figure 3.16 Plan of Lakeside Classroom

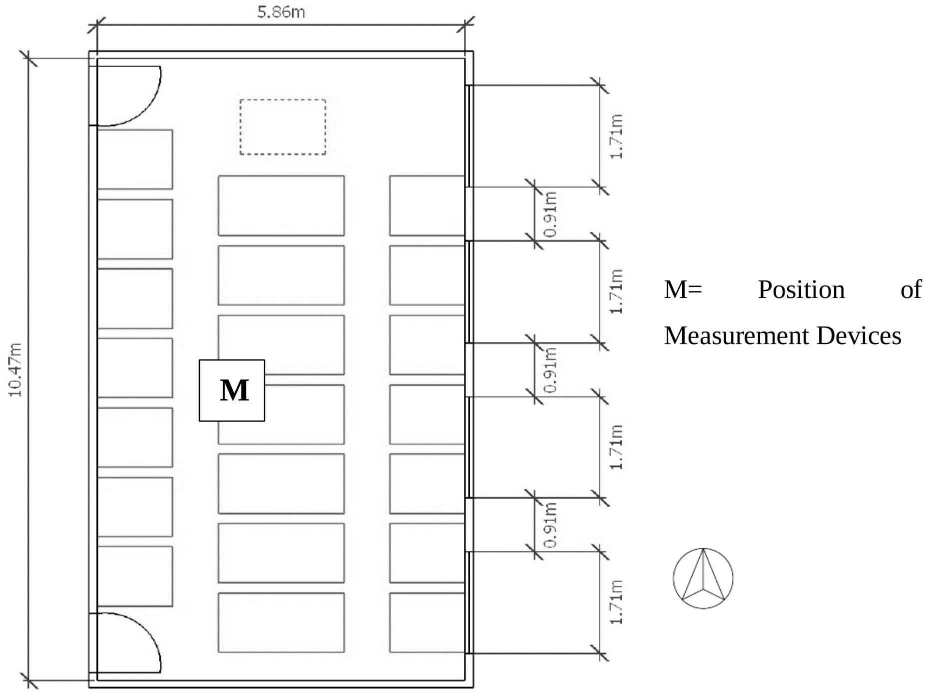
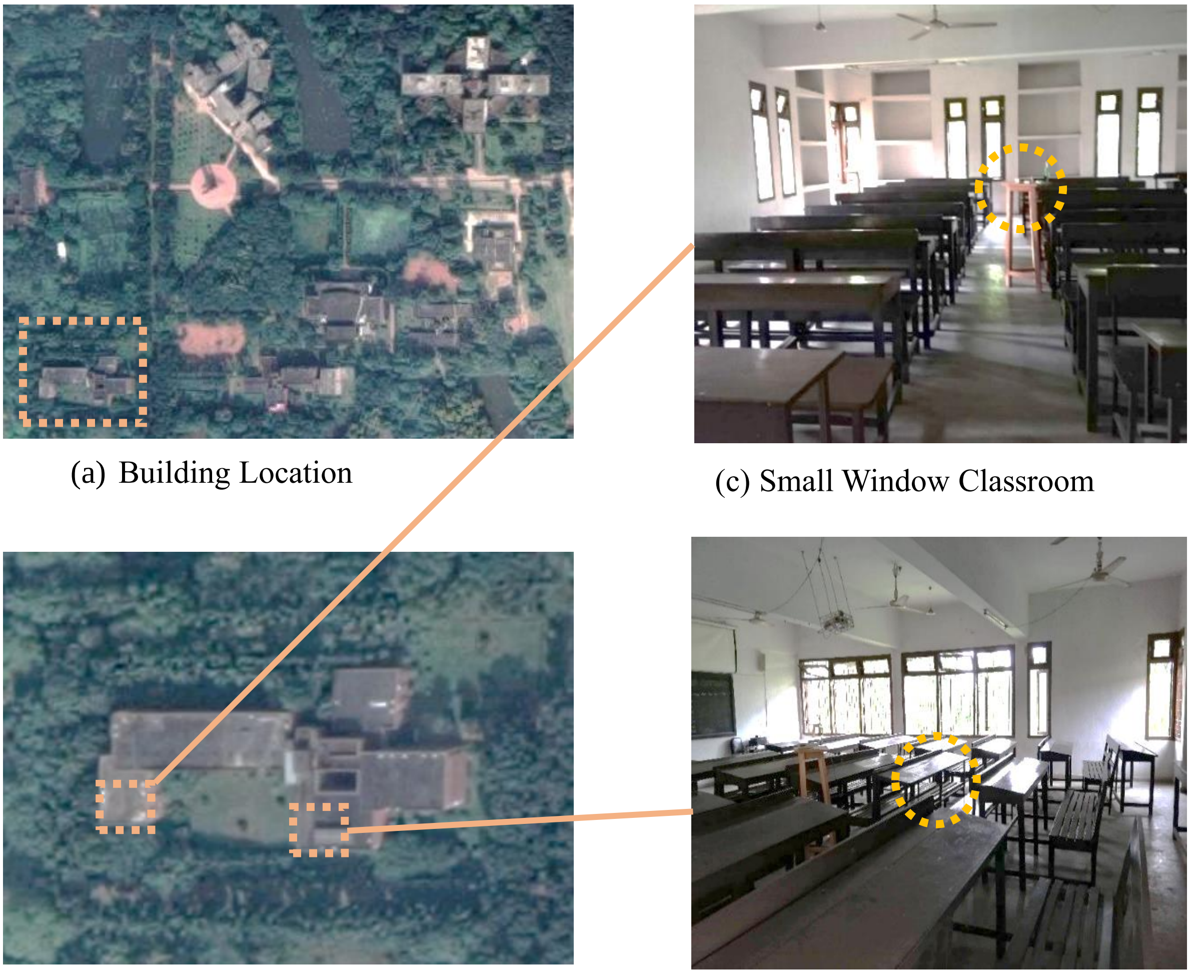


Figure 3.17 Plan of Non-lakeside Classroom

Lakeside Classroom (Figure 3.16) is located on the second floor of a three-storied academic building near a lake of 15000 m^2. In contrast, Non-lakeside Classroom (Figure 3.17) is located on the second floor of a four-storied non-lakeside academic building. The windows of the classrooms are positioned on the east facing wall. However, the window size of the Lakeside Classroom is smaller than the Non-lakeside Classroom. The doors are located on the west facing wall. The lakeside classroom has one door, while the non-lakeside classroom has two doors. East facing walls are the exterior walls for both the classrooms. Ceiling fans are installed in both the classroom.

3.1.4 Case 4: Classrooms with Small Window Area and Large Window Area

For Case 4, two classrooms with different window size in the same building have been selected. Table 3.4 states the key features of the selected classrooms. Figures 3.18, 3.19, and 3.20 present the building, room location, plans and position of measurement devices, respectively.


(a) Building Location

(b) Room Location

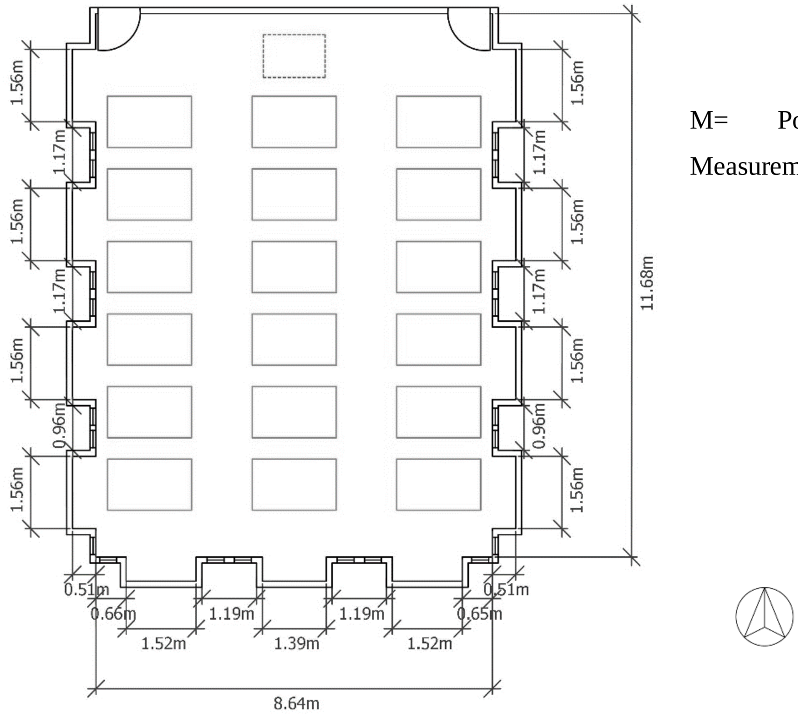
(c) Small Window Classroom

(d) Large Window Classroom

Figure 3. 18 Classroom Locations and Positions of Measurement Devices for Case 4

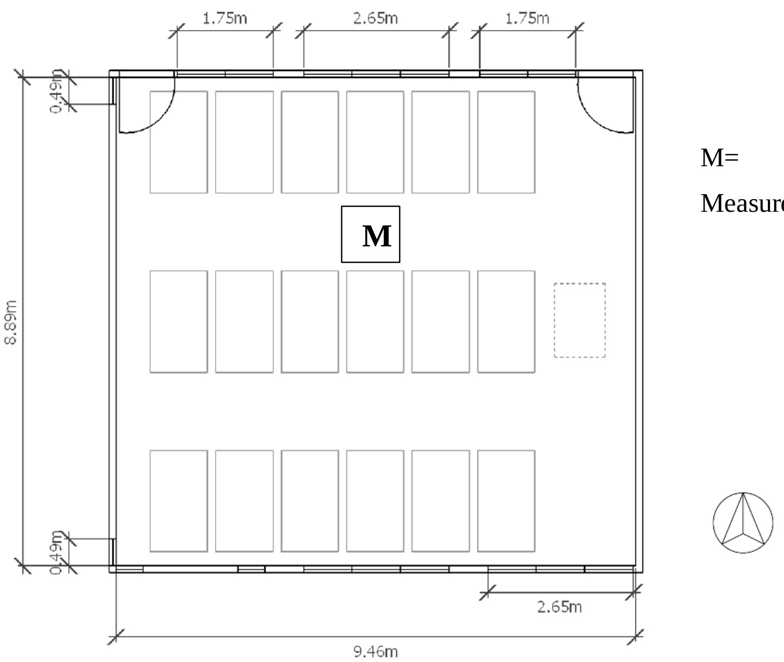
Table 3.4 Major Specifications of Small and Large Window Classrooms

Parameter	Small Window Classroom	Large Window Classroom
Dimensions	11.68 m x 8.64 m x 3.50 m	9.46m x 8.90m x 3.50m
Area	100.90 m^2	84.20 m^2
Volume	353.20 m^3	294.70 m^3
Level	2^{nd} floor	2^{nd} floor
Orientation of Window	East, West, South	North, South, West
Total Window Area	9.40 m^2	17.30 m^2



M= Position of Measurement Devices

Figure 3.19 Plan of Small Window Classroom



M= Position of Measurement Devices

Figure 3.20 Plan of Large Window Classroom

The Small Window Classroom is larger in area and volume than Large Window Classroom. The Small Window Classroom has windows on the east, west, and south facing wall with window to wall ratio (WWR) of 7.3%. While, the Large Window Classroom has windows on the north, south, and west facing wall with 17.3% WWR.

The area and volume of the small window area classroom are relatively higher than the large window classroom. Windows are located on the east, west, and south facing walls in the small window classroom. In large window classroom, windows are located on the north, south, and west facing walls. Doors are located on the north facing walls in both the classrooms. South and west facing walls are the exterior walls for the large window classroom. East, west, and south facing walls are the exterior walls for small window classroom. Ceiling fans are installed in both the classrooms.

3.1.5 Case 5: Studio Type Classroom

In Studio Type Classroom students are usually involved in light laboratory activities like drawing, preparing 2D or 3D Models rather than heavy lifting or strenuous exertion. Major features of the Studio type Classroom are presented in Table 3.5. Figure 3.21 presents the building, and room location of the studio type classroom.

Table 3.5 Major Specifications of Studio Type Classroom

Dimensions	15.9 m x 5.9 m x 3.2 m	**Level**	2^{nd} floor
Area	93.8 m^2	**Orientation of Window**	North
Volume	300.2 m^3	**Window dimensions**	1.6 m x 1.9 m

(a) Building Location

(b) Room Location

Figure 3.21 Building and Room Location of Studio Type Classroom

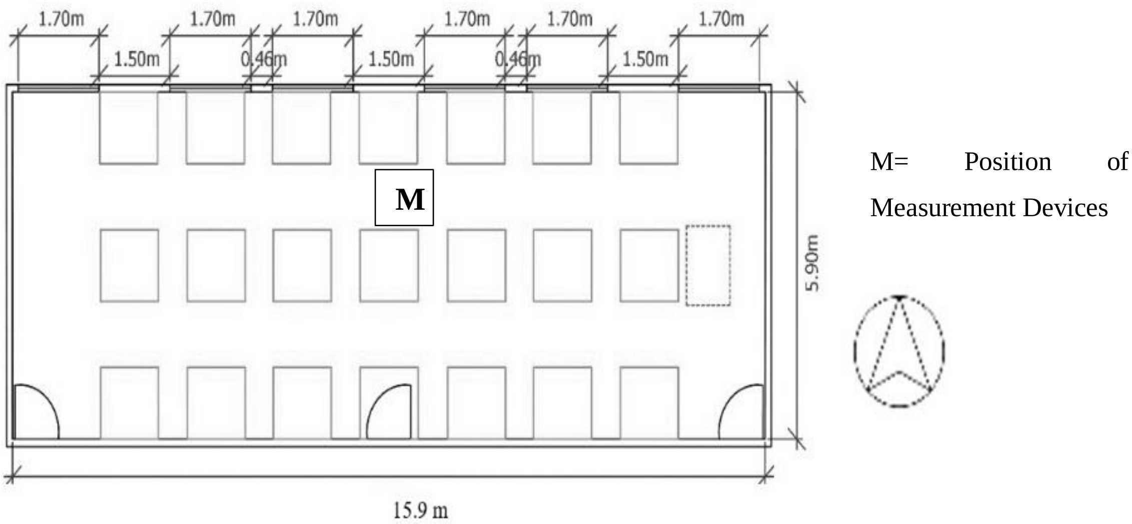


Figure 3.22 Plan of Studio Type Classroom

Figure 3.23 Studio Type Classroom

Figures 3.22 and 3.23 show the plan and position of measurement devices. The Studio type Classroom covers an area of 93.8 m^2 and located on the second floor of a four-storied academic building. The windows are positioned on the north facing wall. The window to wall ratio (WWR) of the entire classroom is 18%. North facing wall is the exterior wall for the studio type classroom. Three doors are located on the south facing wall. Ceiling fans are installed in the classroom.

3.1.6 Case 6: Seminar Library

The seminar Library is attached with every department in Jahangirnagar University, Bangladesh smaller than central library. Students usually stay in Seminar Library for reading, writing, and group study purposes. Table 3.6 states the major specifications of the seminar library. The building, room location, plan, and position of measurement devices are presented in Figure 3.24, and 3.25, respectively.

Table 3.6 Major Specifications of Seminar Library

Parameter	Specifications
Dimensions	10.47 m x 5.86 m x 3.20 m
Area	81.30 m^2
Volume	284.60 m^3
Level	2nd floor
Orientation of Window	West and South
Window dimensions	1.95 m x 1.70 m and 2.00 m x 1.95 m

(a) Building Location

(b) Room Location

M= Position of Measurement Devices

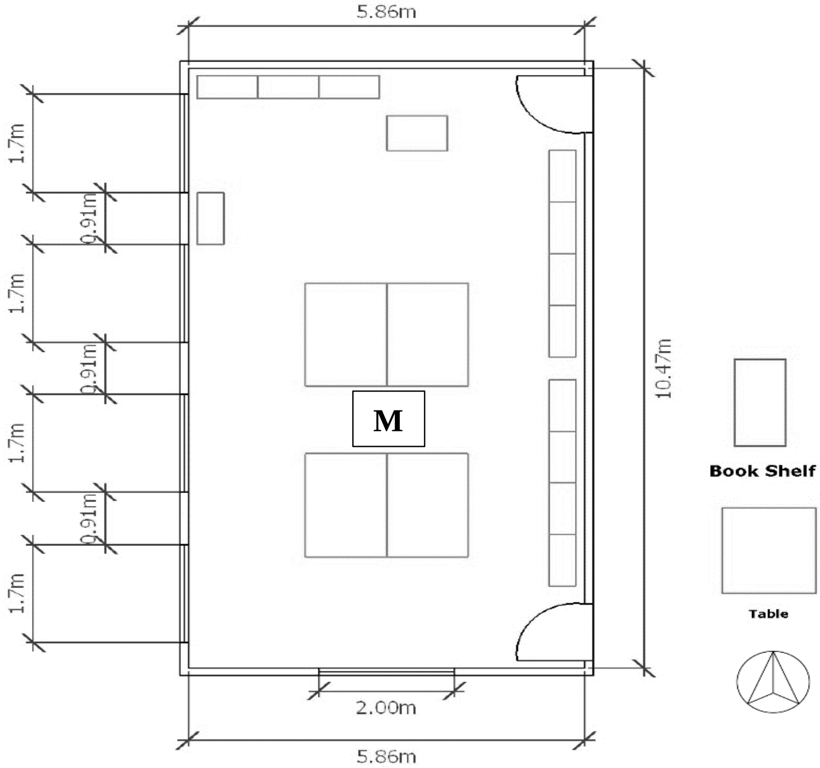


Figure 3.24 Location and Plan of Seminar Library

Figure 3.25 Seminar Library

The seminar library comprises an area of 81.30m^2. four windows are positioned on the east facing wall and one window on the south facing wall. Two doors are located on the east facing wall. West and south facing walls are the exterior walls for seminar library. Ceiling fans are installed in the seminar library.

3.2 Device Set up

Weather data measurement devices are presented in Table 3.7 and Figure 3.26. All the devices (Table 3.7) were placed in the center of the classroom at 1.1 m above the floor. Additionally, one set of similar devices was also placed outside the building (Figure 3.28) to investigate outdoor microclimatic data. Pyranometers were placed in the outdoor location to measure solar irradiation. In outdoor measurement, solar shading has been provided (Figure 3.27) to the thermo hygrometer to obtain more accurate data.

Table 3.7 Weather Data Measurement Devices

Parameter	Instruments	Time Interval	Range	Accuracy
Air temperature	Thermo Recorder TR-72wb	1 min.	0 to 55℃	±0.5℃
Relative humidity	Thermo Recorder TR-72wb	1 min.	10 to 95% RH	±5% RH
Globe temperature	Thermo Recorder TR-45	1 min.	-199 to 1760℃	±(0.5℃ + 0.3% of reading)
Air velocity	Anemometer AM4214SDJ	1 min.	0.2 to 5.0 m/s	± (5% + a) reading

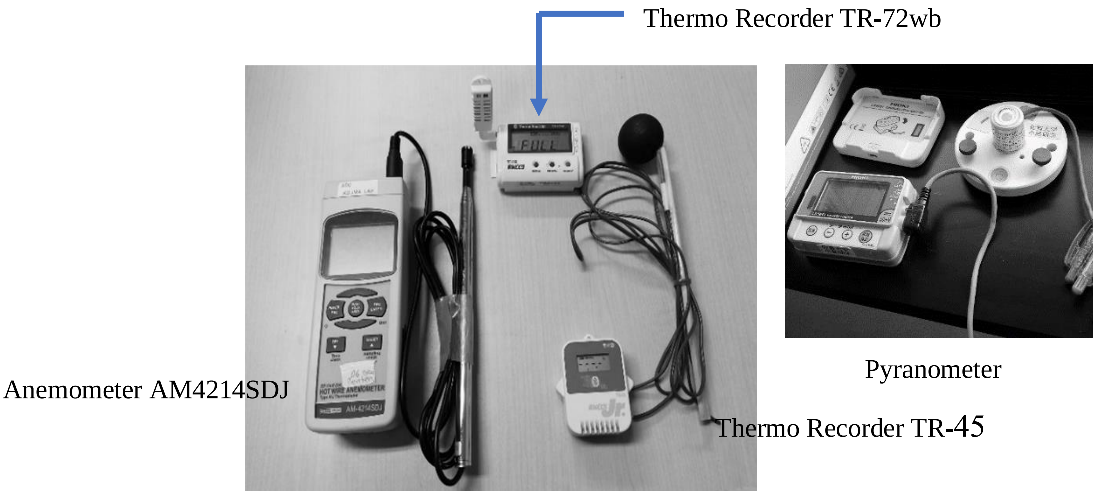


Figure 3.26 Weather Data Measurement Devices

Figure 3.27 Solar Shading of Measurement Devices

Figure 3.28 Locations of Outdoor Weather Data Measurement

3.3 Weather Data Measurement

Field measurement was carried out during typical summer days in May and June 2019. Table 3.8 states the weather data measurement schedule in detail. The weather data were continuously recorded with a 1-minute time interval. All the windows and doors were open during measurement.

Table 3.8 Weather Data Measurement Schedule

Measurement Cases	Measurement Date	Measurement Time
Case 1: Classrooms in different floors of the same building	May 25, 2019	9:30 to 15:00 LST
	May 26, 2019	9:00 to 15:00 LST
	May 27, 2019	9:00 to 15:00 LST
	May 28, 2019	9:00 to 15:00 LST
Case 2: Classrooms surrounded by more tree and less tree	May 13, 2019	9:30 to 15:00 LST
	May 14, 2019	9:00 to 15:00 LST
	May 16, 2019	9:00 to 15:00 LST
	May 19, 2019	9:30 to 15:00 LST
Case 3: Lakeside classroom and Non-lakeside Classroom	May 21, 2019	9:00 to 15:00 LST
	May 22, 2019	9:00 to 15:00 LST
	May 23, 2019	9:00 to 15:00 LST
Case 4: Classrooms with large window area and small window area	May 29, 2019	9:00 to 15:00 LST
	May 30, 2019	9:00 to 15:00 LST
	June 15, 2019	9:00 to 16:00 LST
Case 5: Studio type Classroom	June 11, 2019	9:30 to 16:00 LST
	June 12, 2019	9:00 to 16:00 LST
	June 13, 2019	9:15 to 16:00 LST
Case 6: Seminar Library	June 11, 2019	9:30 to 16:00 LST
	June 12, 2019	9:10 to 16:00 LST
	June 13, 2019	9:00 to 16:00 LST

To assure the investigation more representative, however, data recorded from 9:30 and 9:15 LST on June 11 and June 13 respectively have been used in case of studio type classroom. Besides, for seminar library, data measured from 9:30 LST on June 11 and 9:10 LST on June 12 were used. In case of more tree and less tree classrooms, data measured from 9:30 on May 13 and May 19 were used. From these measured weather data in different university spaces, the indoor and outdoor thermal environment will be examined in Chapter 4.

3.4 Comfort Index Calculation

At first, Mean Radiant Temperature (MRT) was calculated using Equation 3.1 by a self-made program on Engineering Equation Solver (EES). Then, MRT values along with air temperature, air velocity, relative humidity, metabolic rate, and clothing level were put in CBE Thermal Comfort Tool to determine Standard Effective Temperature (SET*). Students are usually involved in reading and writing in seated conditions within the classrooms with a metabolic rate of 1 Met. Simultaneously, 0.5 clo value for a typical summer clothing ensemble was used in the calculation. For Case 5, different value of metabolic rate was used in SET* calculation.

In studio type classroom, students are usually involved in light laboratory activities, e.g., drawing, preparing 2D or 3D Models with a metabolic rate of 1.4 Met (Tyler et al. 2019). The indoor and outdoor thermal comfort in different university space will be evaluated employing SET* in Chapter 5.

3.4.1 Mean Radiant Temperature (MRT)

The temperature of a uniform, black enclosure that exchanges the same amount of heat by radiation with the occupant as the actual surroundings is called mean radiant temperature. It is a single value for the entire body and accounts for long-wave mean radiant temperature and short-wave mean radiant temperature (ASHRAE, 2017). Mean radiant temperature can be obtained by using following equation 3.1 (Szokolay, 2008).

$$MRT = GT\left(1 + 2.35\sqrt{v}\right) - 2.35.DBT\sqrt{v} \qquad \text{[Eqn. 3.1]}$$

Here, GT is globe temperature, DBT is dry bulb temperature, and v is air velocity.

3.4.2 Standard Effective Temperature (SET*)

SET* proposed by Gagge developed based upon a dynamic two-node model (core node and skin node) of human temperature regulation has also been widely applied in the field of thermal environment and comfort (Ye, Yang, Chen, Li, 2003, and Zhang, Wang, Chen, Zhang and Meng, 2010). SET* is the temperature of an imaginary environment at 50% relative humidity (RH), < 0.1 ms^{-1} average air speed (V_a), and mean radiant temperature is equal to average air temperature, in which the total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is the same as that from a person in the actual environment with actual clothing and activity level (ASHRAE, 2017). Table 3.9 states the SET* index levels and thermal sensations.

Table 3.9 SET* Index Levels and Thermal Sensation

SET* (^{o}C)	Sensation	Physiological state of sedentary person
>37.5	Very hot, very uncomfortable	Failure of regulation
34.5– 37.5	Hot, very unacceptable	Profuse sweating
30.0–34.5	Warm, uncomfortable, unacceptable	Sweating
25.6–30.0	Slightly warm, slightly unacceptable	Slight sweating
22.2–25.6	Comfortable and acceptable	Neutrality
17.5–22.2	Slightly cool, slightly unacceptable	Vasoconstriction
14.5–17.5	Cool and unacceptable	Slow body cooling
10.0–14.5	Cold, very unacceptable	Shivering

Source: Adopted from Parsons, 2006

SET* value ranges between 10 to 14.5°C indicates a “Cold” sensation which is very unacceptable. In the contrary, 34.5 to 37.5°C orbit of the SET* value means “Hot” in sensation and very unacceptable. The sensation will be “Very Hot” if the value is found greater than 37.5°C, and people will feel very uncomfortable. The calculated SET* value within the domain of 22.2 to 25.6°C is specified as “Comfortable” and acceptable by the model (Parsons, 2006). To measure the equivalence of any combination of environmental factors, and human factors e.g., clothing insulation and metabolic rate, SET* provides a rational foundation (Auliciems and Szokolay, 2007).

3.5 Simulation for Evaluating the Outdoor Weather Effects in Indoor Thermal Environment

To examine the effects of outdoor environmental settings on indoor thermal environment, simulation study has been carried out. The process of simulation study can be showed as in Figure 3.29.

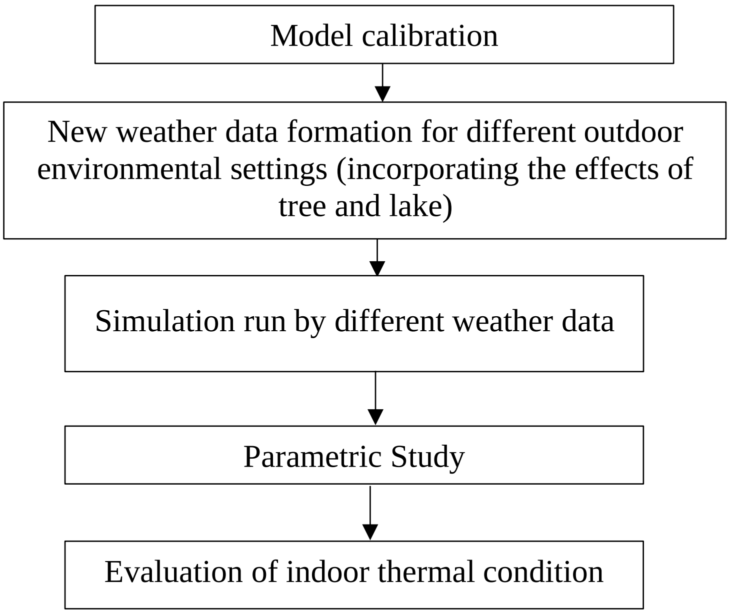


Figure 3.29 Procedure of Simulation Study

EnergyPlus 8.7 has been employed to run simulation study. The procedure of simulation study will be described elaborately in Chapter 6. Initially classroom model has been calibrated to validate the weather data. The simulation results and the measurement results have been compared. After finding the matching trend between simulation and measurement results further simulations have been run with different weather data incorporating the effects of tree and lake. Then considering construction material a parametric study has been conducted. Finally, the indoor thermal environment has been evaluated considering different outdoor weather conditions and parametric study.

3.6 Conclusion

Specifications of field measurement sites have been described. The weather measurement devices have been set up in each site according to the protocol of ASHRAE-55, Standards. Weather data measurement was conducted in typical summer days during the months of May and June.

To evaluate thermal comfort, Standard Effective Temperature (SET*) has been calculated combining weather factors and human factors. In studio type classroom, students are usually involved in light laboratory activities. So, the metabolic rate value of 1.4 met is used in SET* calculation. In other cases, 1.0 met has been used considering the students were involved in reading and writing. Typical summer clothing ensemble has been used in the calculation for all cases.

To examine the effects of outdoor environmental setting on indoor thermal environment simulation study has been conducted. Preliminary model has been selected finding matching trend between measured and simulated results after calibration. Parametric study has been carried out by calibrated model to find out the optimum design modification. Further simulation has been run with different weather data to evaluate the influence of tree and lake on indoor thermal environment. The entire methodology of this study has been illustrated in Figure 3.30.

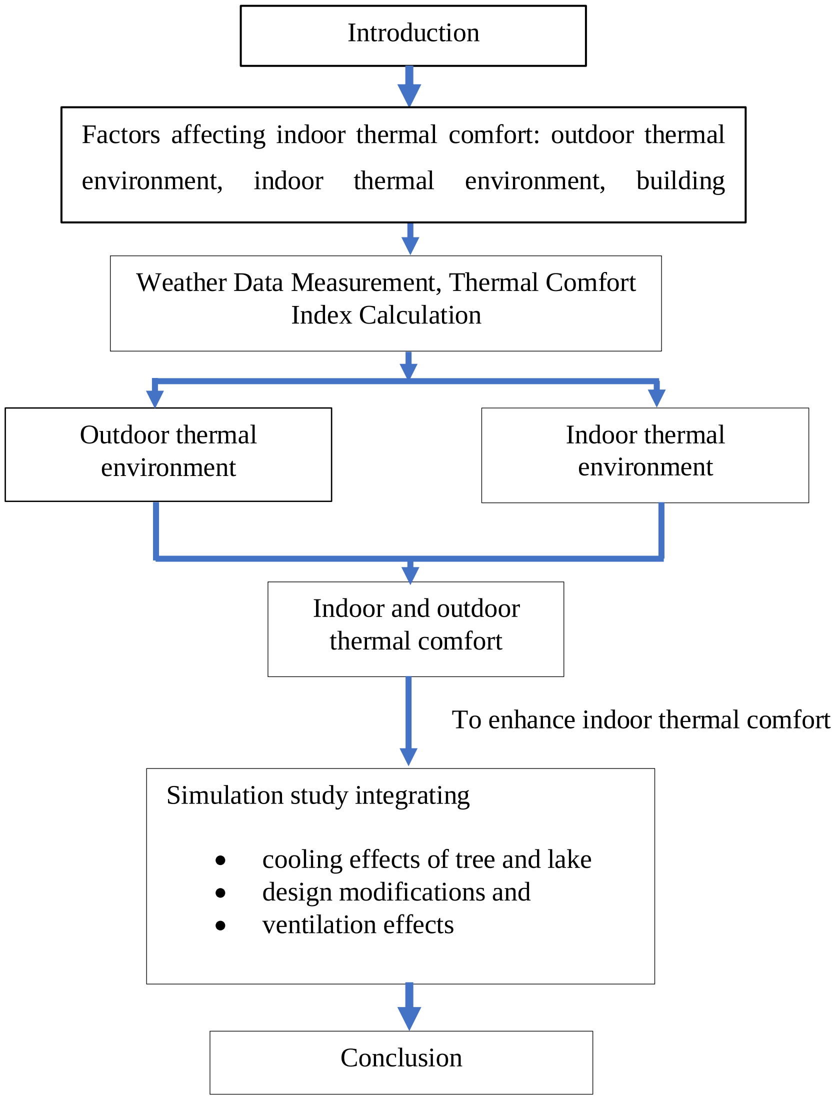


Figure 3.30 Study Methodology

Chapter 4

Thermal Environment Analysis of University Spaces Based on Measurement

To enhance thermal comfort condition, proper investigation of thermal environment is essential. Therefore, field measurements have been carried out in different types of university spaces in Jahangirnagar University, Bangladesh. Weather data e.g., air temperature, globe temperature, relative humidity, air velocity, and solar irradiation were measured in different university spaces. This chapter will present the major features of the thermal environment upon which thermal comfort condition will be analyzed in Chapter 5.

4.1. Case 1: Thermal Environment Comparison of Classrooms in Different Floors of the Same Building

Figures 4.1, and 4.2 depict the diurnal distribution of air temperature, and relative humidity, respectively in different measurement dates. The outdoor weather was overcast on May 25. Consequently, the indoor and outdoor air temperature found lower compared to other measurement dates. The lowest indoor air temperature (T_{ai}) was recorded as 26.5^{o}C in 1st floor classroom, 27.6^{o}C in 2nd floor classroom, and 28^{o}C in 3rd floor classroom. The mean T_{ai} of 2nd floor Classroom was lower than 1st floor and 3rd floor Classroom except on May 25. However, the T_{ai} of 1st floor Classroom was lower than 2nd floor Classroom around up to 10:00 Local Standard Time (LST) other than May 25. The minimum T_{ai} of 1st floor Classroom was recorded as 29^{o}C on May 26, 30^{o}C on May 27, and 29.6^{o}C on May 28. Apart from May 25, the mean T_{ai} of 2nd floor Classroom was lower than 1st floor and 3rd floor Classroom. Being located at the top floor of a three-storied building, the 3rd floor Classroom was exposed more to solar heat gain. Consequently, the T_{ai} of 3rd floor Classroom was higher than other Classrooms. The highest T_{ai} of 3rd floor Classroom was measured as 34.5^{o}C on May 28, 34.1^{o}C on May 27, 32.8^{o}C on May 26, and 29^{o}C on May 25.

The outdoor air temperature (T_{ao}) was higher than T_{ai} of classrooms located in three different floors other than May 25. On that date, the mean T_{ao} was 0.7^{o}C higher than 1st floor Classroom, 0.3^{o}C and 0.7^{o}C lower than 2nd floor and 3rd floor Classroom respectively. The minimum T_{ao} was 26.3^{o}C on May 25, followed by 31.2^{o}C on May 28. The maximum T_{ao} was recorded as 36.8^{o}C on May 26 and 27, and 35.8^{o}C on May 28. On May 26, the T_{ao} tended to increase around 12:00 LST. At the same period, an increase in the T_{ai} was observed also. Besides, the T_{ao} was started to decrease between 11:52 and 12:15 LST on May 27 and consequently the T_{ai} of the classrooms were also dropped during that period.

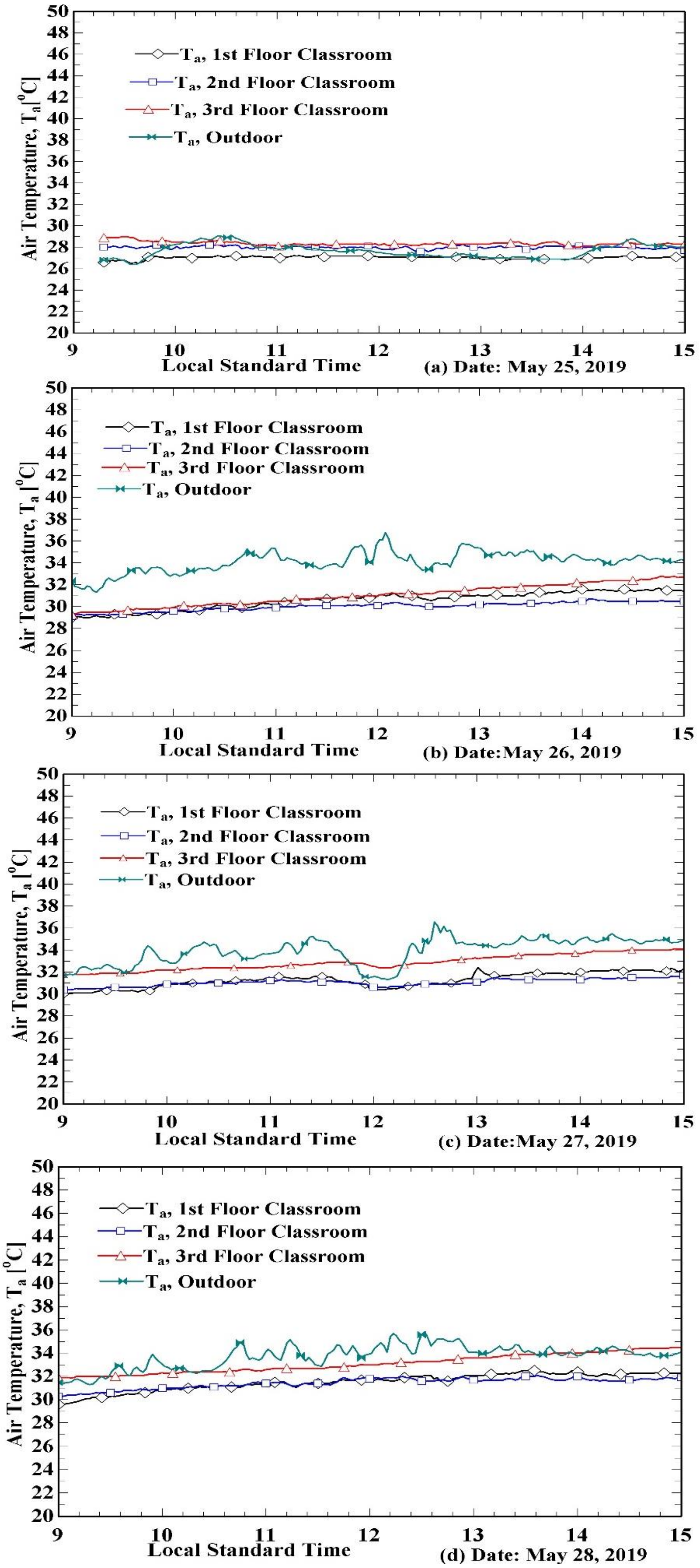


Figure 4.1 Diurnal Distribution of Indoor and Outdoor Air Temperature of Case 1

Both the indoor and outdoor Relative Humidity (RH_i and RH_o) were found comparatively in a steady trend (Figure 4.2) on May 25. The mean RH_i was 80.2% in 1st floor Classroom, 74.1% in 2nd floor Classroom, and 72% in 3rd floor Classroom on that date. Inside the 3rd floor Classroom, the RH_i values were found lower during all the measurement dates in response to higher air temperature. The minimum RH_i was measured as 65% on May 28, followed by 68% on May 27 in 3rd floor Classroom. While the maximum RH_i was 80% on May 26 and 78% on May 27. In 2nd floor Classroom, the mean RH_i was lower on May 25 (74.1%) and May 28 (74.3%). The minimum RH_i was measured as 71% on May 25, and 72% on May 28; whereas the maximum RH_i was 85% on May 27 and 82% on May 26 in that classroom. The 1st floor Classroom possesses a higher RH_i than other classrooms in all measurement dates except May 27. The highest RH_i was 87% on May 27, 85% on May 26, and 84% on May 25. While the lowest RH_i was 72% on May 27 and 28 in that classroom.

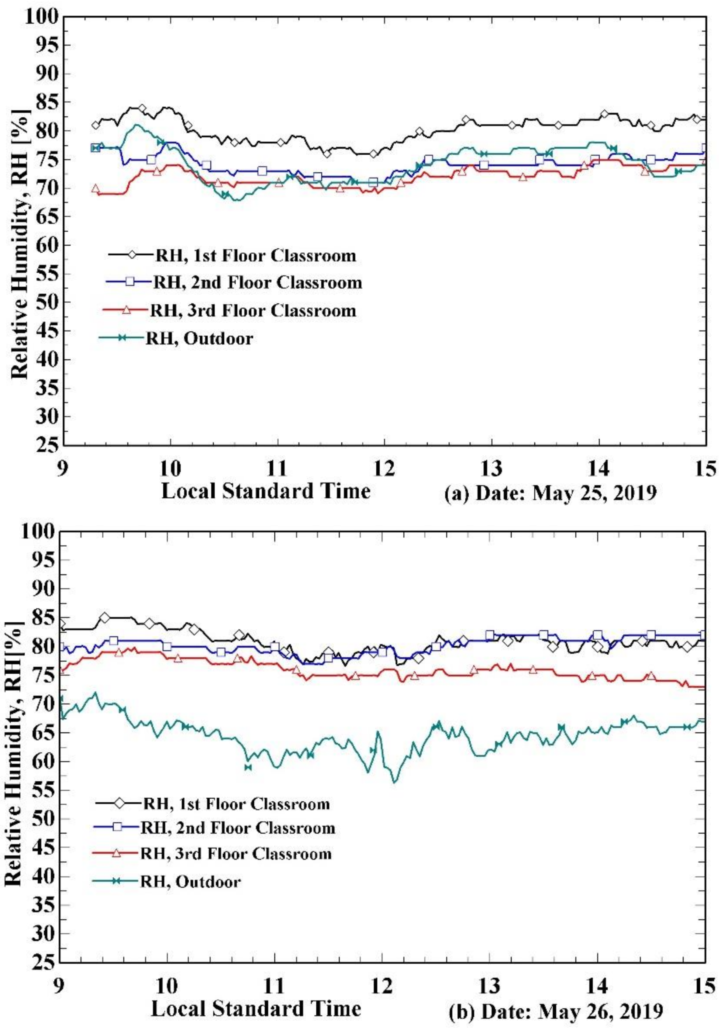


Figure 4.2 Diurnal Distribution of Indoor and Outdoor Relative Humidity of Case 1

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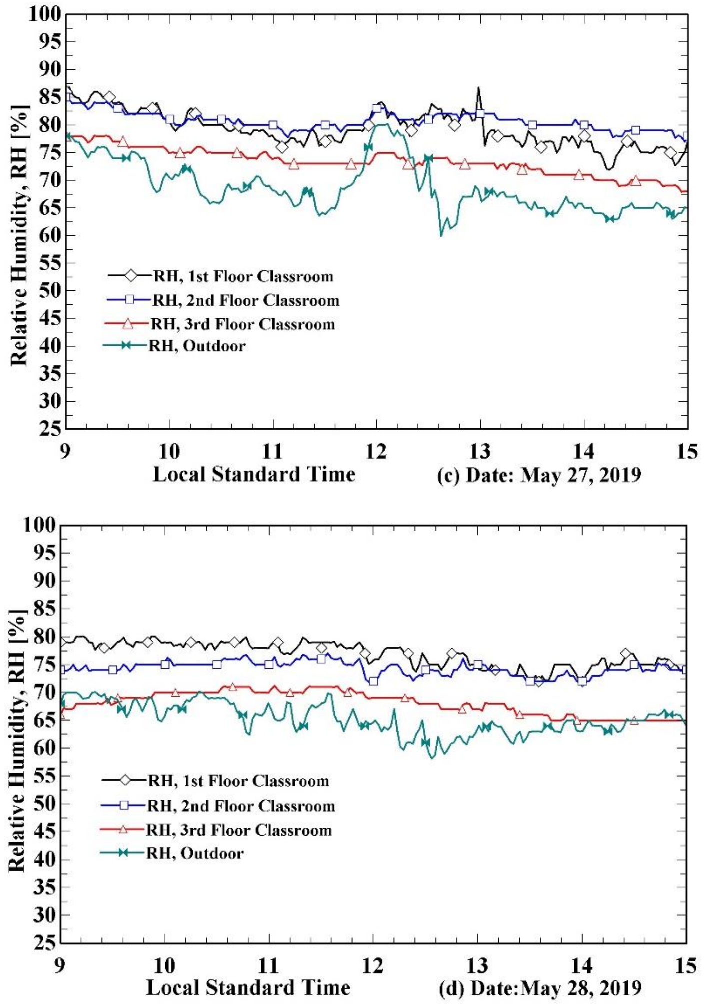


Figure 4.2 Diurnal Distribution of Indoor and Outdoor Relative Humidity of Case 1

Other than May 25, the Outdoor Relative Humidity (RH_o) was lower than its indoor counterpart. The mean RH_o was calculated as 74.1% on May 25, 64.5% on May 26, 68.8% on May 27, and 65.3% on May 28. In response to the higher outdoor air temperature, the minimum RH_o was measured as 56% on May 26, and 58% on May 28. While the maximum RH_o was found 81% on May 25, and 80% on May 27. Table 4.1 presents the indoor and outdoor air velocity of Case 1.

Table 4.1 Indoor and Outdoor Air Velocity (V_a), Different Floor Classrooms

Date	1st Floor V_a [ms^{-1}]	2nd Floor V_a [ms^{-1}]	3rd Floor V_a [ms^{-1}]	Outdoor V_a [ms^{-1}]
May 25	0.10	0.00	0.00	0.86
May 26	0.09	0.00	0.00	0.14
May 27	0.26	0.00	0.00	0.41
May 28	0.14	0.00	0.00	0.55

The air velocity inside 1st Floor's Classroom was notable during all the measurement dates. The maximum mean air velocity was calculated as 0.26 ms^{-1} on May 27 and 0.14 ms^{-1} on May 28. The highest air velocity was recorded on May 27 as 1.46 ms^{-1}, followed by 0.87 ms^{-1} on May 28 when ceiling fans were in operation. The mean air velocity was very low inside other classrooms located on the 2nd and 3rd floor. However, the highest air velocity was recoded as 0.68 ms^{-1} in 2nd floor Classroom, and 0.45 ms^{-1} in 3rd floor Classroom on May 28 when ceiling fans were in operation. Ceiling fans were switched on between 12:35 and 12:45 LST in 1st floor, 12:53 and 13:00 LST in 2nd floor, and 13:08 and 13:18 LST on May 28. Apart from those periods, the ceiling fans were switched off. Doors and windows were open during the measurement periods. Larger window area (19.4m^2) of 1st floor's Classroom augmented the air circulation compared to other classrooms.

The outdoor air velocity was much higher on May 25. The mean outdoor air velocity was calculated as 0.86 ms^{-1} on May 25, 0.55 ms^{-1} on May 28, and 0.41 ms^{-1} on May 27. The maximum outdoor air velocity was measured as 2.93 ms^{-1} on May 25, followed by 2.25 ms^{-1} on May 27. The outdoor air velocity was found lower on May 26. On that date, the minimum outdoor air velocity was measured as 1.15 ms^{-1} with a mean value of 0.14 ms^{-1}.

4.2. Case 2: Thermal Environment Comparison between Classrooms Surrounded by More Tree and Less Tree

The outdoor air temperature and solar irradiation are plotted in Figure 4.3. The solar irradiation and outdoor air temperature seem to be correspondence. The solar irradiation of more tree classroom was lower due to tree effect. consequently, the outdoor air temperature was also lower than less tree classroom.

Indoor and outdoor air temperature and relative humidity of Classroom surrounded by more tree and Classroom surrounded by less tree are plotted in Figure 4.4 and Figure 4.5, respectively. The indoor Air temperature (T_{ai}) and Relative Humidity (RH_i) progress steadily in both classrooms. However, higher fluctuations were observed in outdoor Air temperature (T_{ao}) and Relative Humidity (RH_o) of Classroom surrounded by less tree.

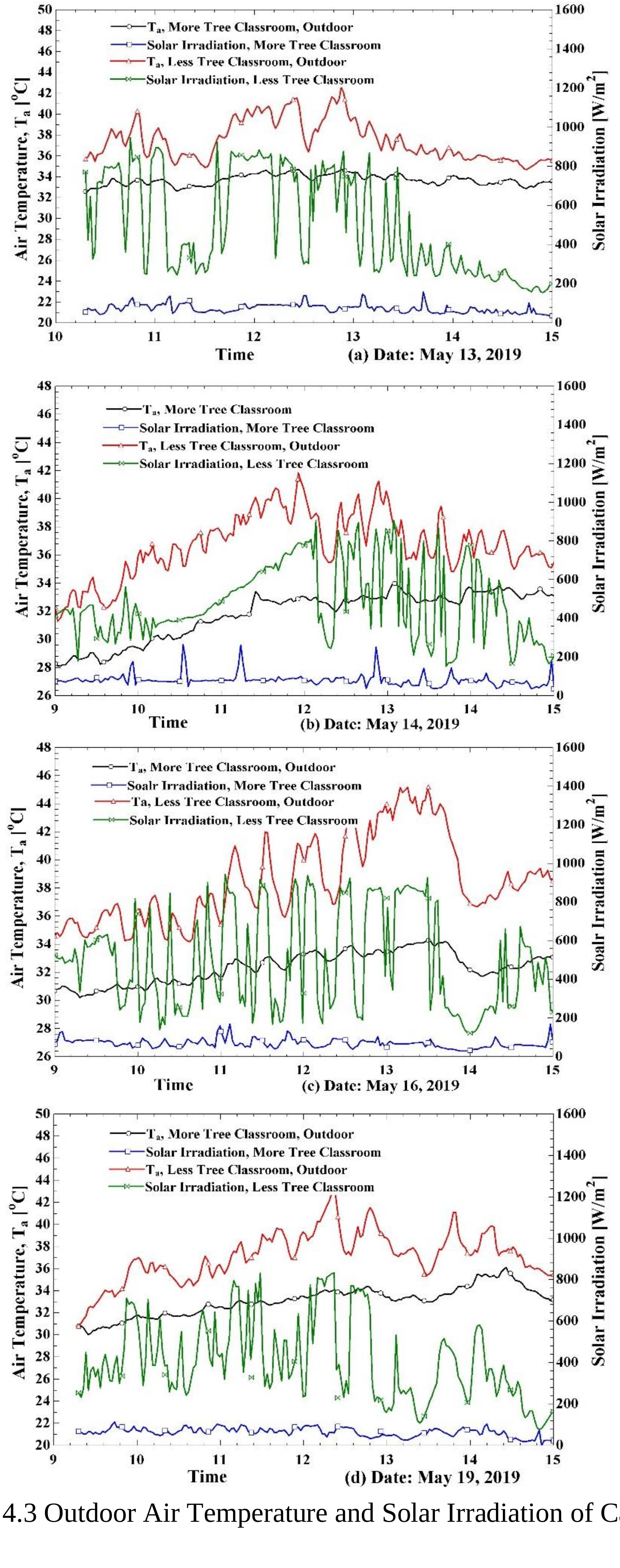


Figure 4.3 Outdoor Air Temperature and Solar Irradiation of Case 2

4.2.1 Weather Parameters for Classroom Surrounded by More Tree (1525.3 m^2)

The T_{ao} was recorded higher than the T_{ai} in maximum time except some periods on May 14 and May 16. On May 14, the T_{ao} was found lower than T_{ai} up to 10:30 LST due to cloudy weather. T_{ao} and T_{ai} values were remained almost same up to 10:00 LST on May 16. The outside weather was slightly cloudy during this time. Both T_{ao} and T_{ai} found lower in the morning and started to increase as the time progresses especially from the noon (12:00 LST). The T_{ai} found higher on May 13 with the highest recorded value of 33.4°C followed by 32.5°C on May 16 and May 14. The overall T_{ai} values on May 19 were lower up to 11:00 LST than other measurement dates with a minimum value of 29°C. Higher T_{ao} was observed on May 13 with the highest value of 34.8°C followed by May 19. The average T_{ao} on May 14 was determined as the lowest (31.8°C) with a minimum value recorded as 28.1°C.

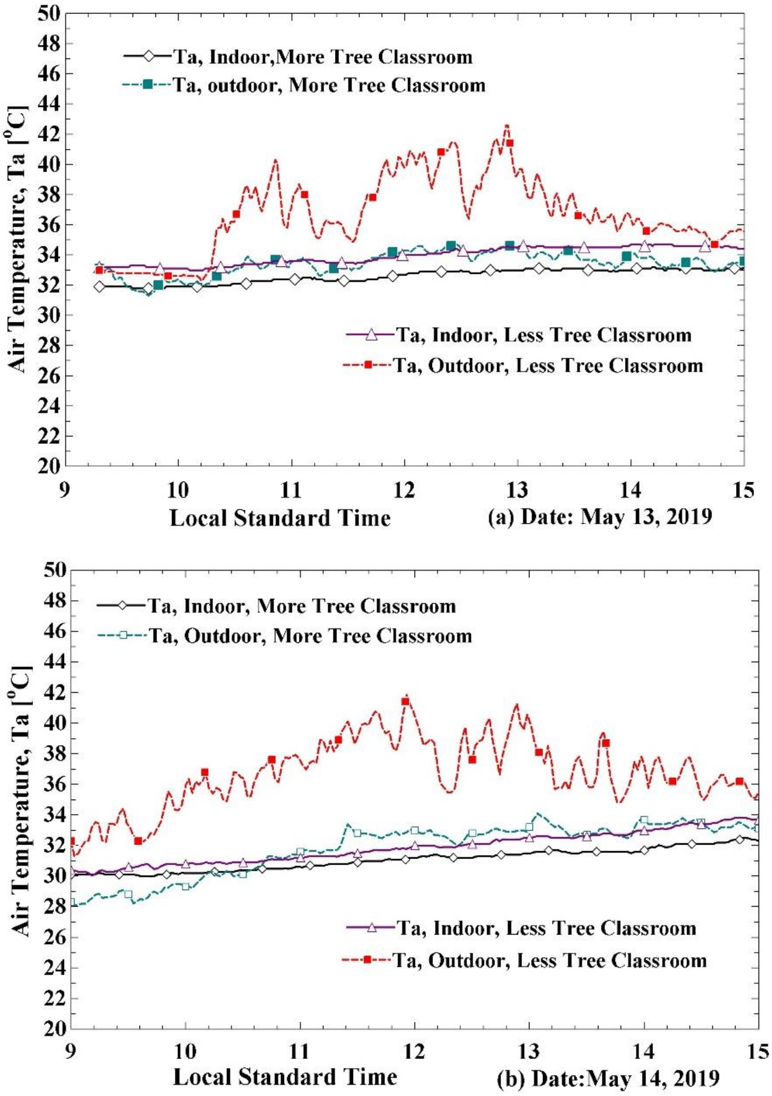
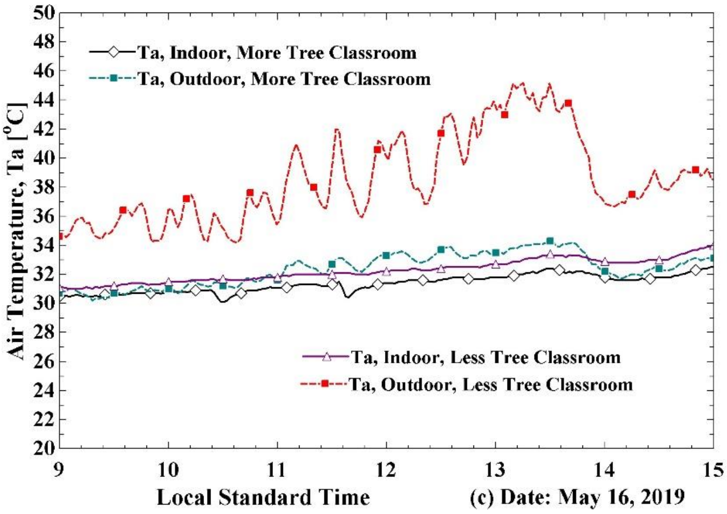


Figure 4.4 Diurnal Distribution of Air Temperature of Case 2 [Continue in next page]



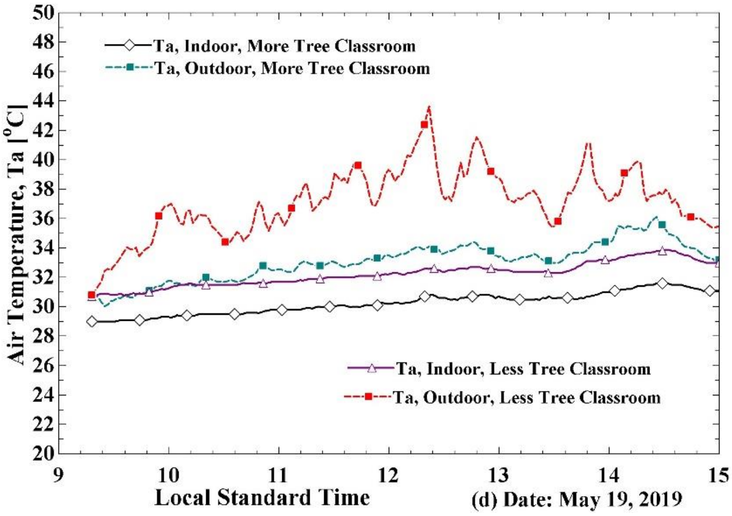


Figure 4.4 Diurnal Distribution of Air Temperature of Case 2

The RH_i trend was steady than RH_o. Both RH_i and RH_o values were found higher in the morning and started to decrease as T_{ao} and T_{ai} increase with the progress of time. The average RH_i (85%) was much higher on May 19 than other measurement dates with a maximum value of 89%. The minimum RH_i was measured on May 16 as 58% with an average of 71.6%. The measured RH_o values were lower than RH_i in all dates. The average RH_o was lower (67.4%) on May 13 and higher (74.3%) on May 19. However, the lowest RH_o was recorded as 51% on May 16 followed by 58% on May 14. The maximum RH_o was found on May 19 as 81%.

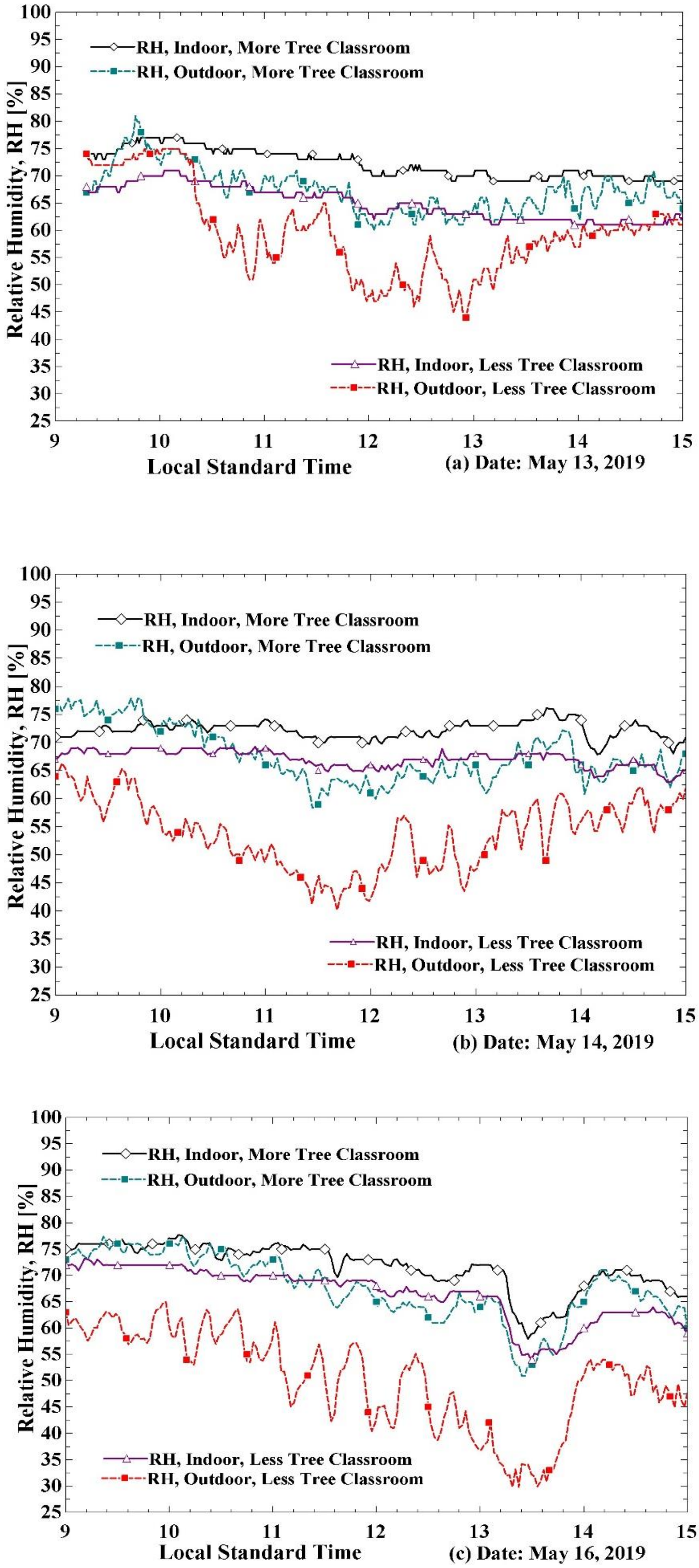


Figure 4.5 Diurnal Distribution of Relative Humidity of Case 2 [Continue in next page]

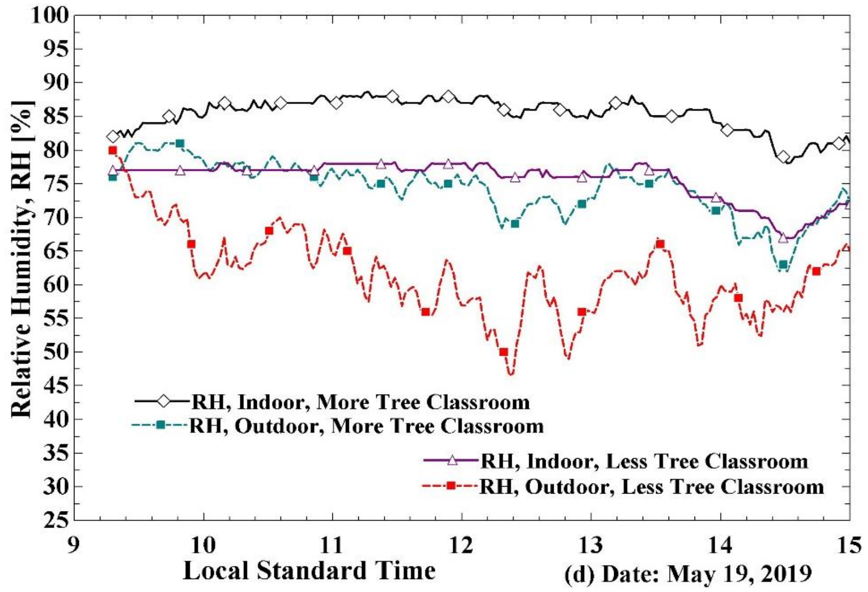


Figure 4.5 Diurnal Distribution of Relative Humidity of Case 2

Table 4.2 states the indoor and outdoor air velocity of more tree and less tree classrooms. The air inside the classroom was found tranquil (Table 4.2) in most of the measurement periods. The highest air velocity was recorded as 1.07 ms^{-1} on May 19 with a higher average value of 0.01 ms^{-1}. Ceiling fans were in operation from 13:41 to 13:52 LST on May 19. Apart from this period, ceiling fans were switched off and the windows and doors of the classroom were remained open.

The outdoor air velocity was higher and changed more frequently than the indoor counterpart. The average outdoor air velocity was found higher (0.5 ms^{-1}) on May 13 followed by May 14 and 16 (0.3 ms^{-1}). On May 13, the outdoor air velocity was very low up to 10:14 and started to increase thereafter. The highest outdoor air velocity was recorded as 3.47 ms^{-1} on May 13. Compared to other dates, the average outdoor air velocity was found lower (0.2 ms^{-1}) on May 19.

Table 4.2 Indoor and Outdoor Air Velocity, More Tree, and Less Tree Classroom

Date	**Average Indoor Air Velocity [ms^{-1}]**		**Average Outdoor Air Velocity [ms^{-1}]**	
	More Tree Classroom	Less Tree Classroom	More Tree	Less Tree
May13	0.00	0.00	0.50	0.50
May 14	0.00	0.00	0.30	0.80
May 16	0.00	0.00	0.30	0.60
May 19	0.00	0.02	0.20	0.60

4.2.2 Weather Parameters for Classroom Surrounded by Less Tree (307.5 m^2)

The average T_{ai} was the highest (33.9°C) on May 13. The maximum T_{ai} was recorded as 34.7°C on that date (Figure 4.4). The average T_{ai} was found lower (31.8°C) on May 14 with a minimum T_{ai} of 30.1°C. On May 16, the average T_{ao} was higher (38.6°C) than other measurement dates with a maximum T_{ao} value of 45.2°C. The lowest T_{ao} was found on May 19 as 30.8°C during the morning period. The T_{ao} values were higher than T_{ai} in most of the measurement periods except up to 10:15 LST on May 13 due to the appearance of cloud. During this period, the T_{ai} was slightly higher than T_{ao}. Wild fluctuations of T_{ao} were observed on all the measurement dates. The T_{ai}, in contrast, forms a steady trend with the progress of time.

The RH_o fluctuates in a greater extent compared to the RH_i (Figure 4.5). During morning periods, the RH_i values were higher and started to decline gradually in response to the increase of T_{ai} as the time progresses. The lowest average of RH_i was determined on May 13 as 64.9% followed by 66.5% on May 16. However, the lowest RH_i was recorded as 54% on May 16 followed by 61% on May 13. Apart from May 13 (up to 10:15 LST) the RH_o was much lower than RH_i. The minimum RH_o was found on May 16 as 29% with a lower average value of 50.2%. The highest T_{ao} was also recorded as 45.1°C on that date. The highest RH_o (80%) was evident on May 19 along with the lowest T_{ao} of 30.8°C.

The average indoor air velocity was much lower than its outdoor counterpart. Air inside the classroom was remained still in most of the measurement periods. Doors and windows were opened, and ceiling fans were switched off. On May 19, ceiling fans were in operation from 13:26 to 13:34 LST and a maximum air velocity was recorded as 0.74 ms^{-1}. The highest average indoor air velocity was 0.02 ms^{-1} on May 19 followed by 0.01 ms^{-1} on May 13.

The average outdoor air velocity was the highest (0.80 ms^{-1}) on May 14 followed by 0.60 ms^{-1} on May 16 and 19. However, the highest outdoor air velocity was recorded on 3.48 ms^{-1} on May 13, and then 3.11 ms^{-1} on May 19. Both the indoor and outdoor air velocity of Classroom surrounded by less tree were recorded higher than the classroom surrounded by more tree. Sparsely planted a smaller number of trees augment the air velocity to some extent in case of classroom surrounded by less tree.

4.3. Case 3: Thermal Environment Comparison between Lakeside Classroom and Non-lakeside Classroom

The outdoor air temperature and solar irradiation of the lakeside and non-lakeside classroom are plotted in Figure 4.6. The outdoor air temperature and solar irradiation of the lakeside classroom found lower than the non-lakeside classroom.

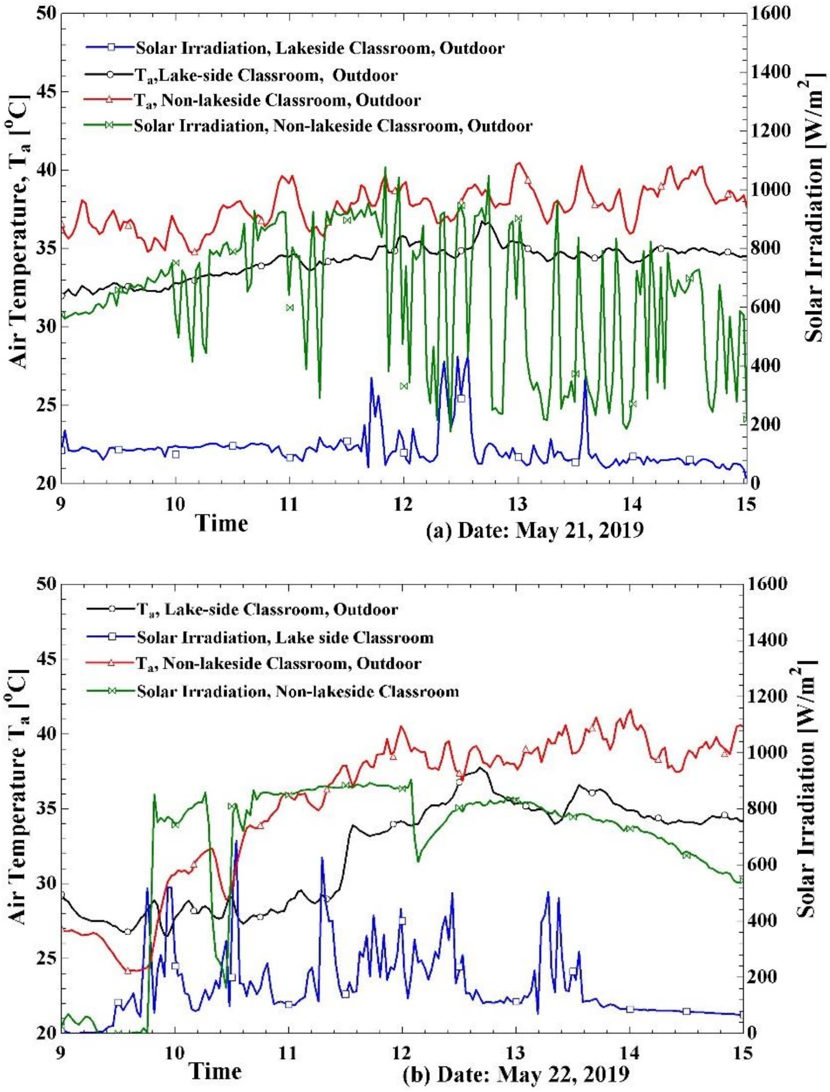


Figure 4.6 Outdoor Air Temperature and Solar Irradiation of Case 3 [Continue in next page]

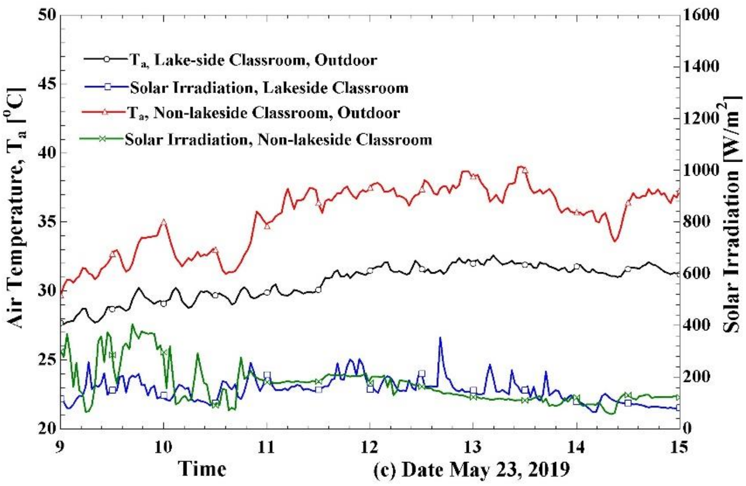


Figure 4.6 Outdoor Air Temperature and Solar Irradiation of Case 3

Figure 4.7 and Figure 4.8 present the indoor and outdoor air temperature (T_{ai} and T_{ao}), and relative humidity (RH_i and RH_o) respectively in different measurement dates. The outdoor environmental parameters e.g., air temperature, relative humidity, and air velocity, fluctuated more than those indoor counterparts.

4.3.1. Weather Parameters for Lakeside Classroom

The air temperature inside the Lakeside Classroom (T_{ai}) was found lower in the morning, especially up to 10:11 LST on May 22, and up to 10:27 LST on May 23. The T_{ai} usually started to increase steadily with the progress of time in all measurement dates. The overall T_{ai} was found higher (average T_{ai} 33.3°C) on May 21 when the maximum T_{ai} was measured as 34.6°C. On May 23, the average T_{ai} was lower (30.5°C) than other measurement dates, with a minimum T_{ai} value of 28.9°C. The T_{ao} was lower than T_{ai} up to 11:00 LST on May 22 and 23. On average, the T_{ao} was 1.8°C lower than T_{ai} up to 11:00 LST on May 22, and 0.6°C on May 23. The outdoor weather was overcast up to 11:00 LST on May 22. The lowest T_{ao} was measured as 26.5°C on May 22, followed by 27.6°C on May 23. Apart from this, the T_{ao} was higher than T_{ai}. On May 21, the T_{ao} was 0.9°C higher than T_{ai}. The highest T_{ao} was 37.8°C on May 22 and 36.8°C on May 21 during the afternoon period.

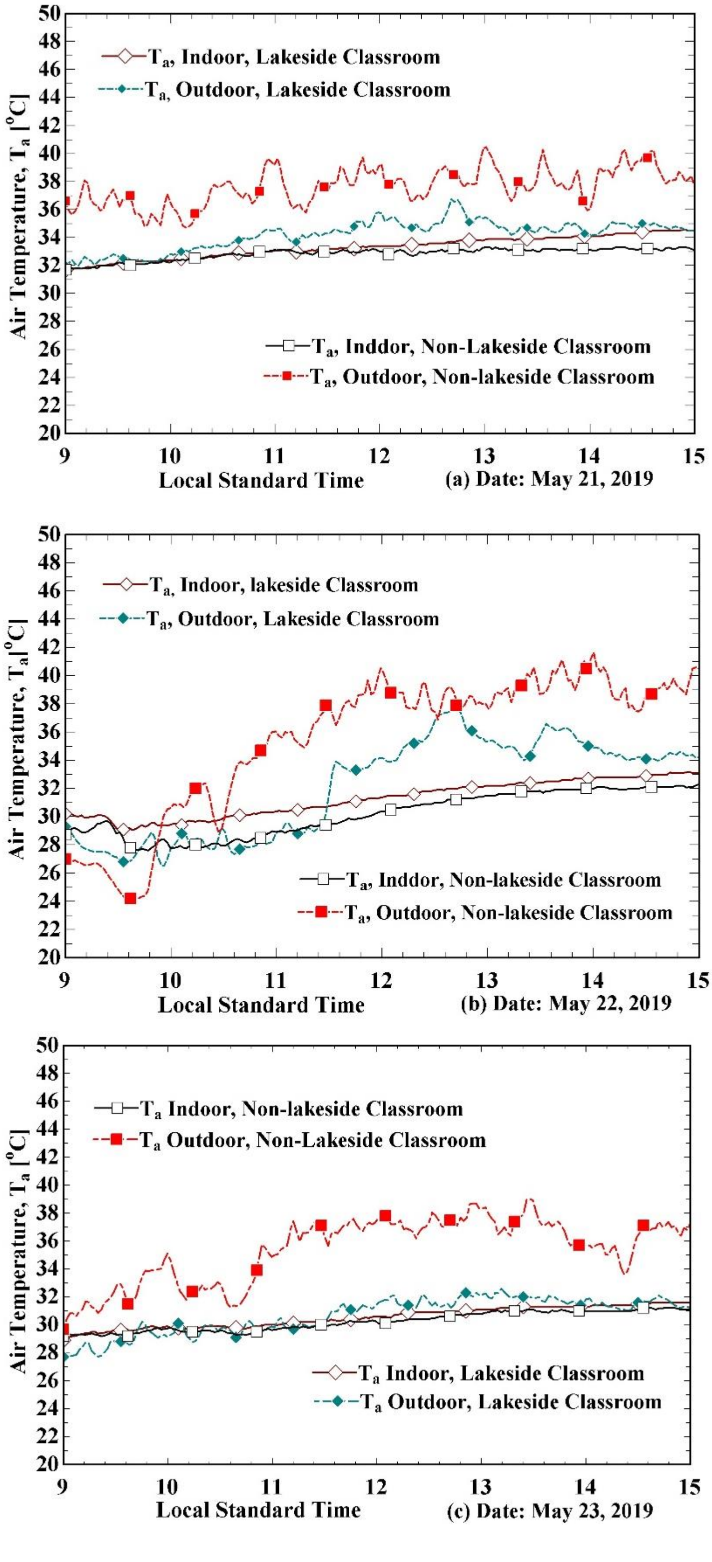


Figure 4.7 Diurnal Distribution of Indoor and Outdoor Air Temperature of Case 3

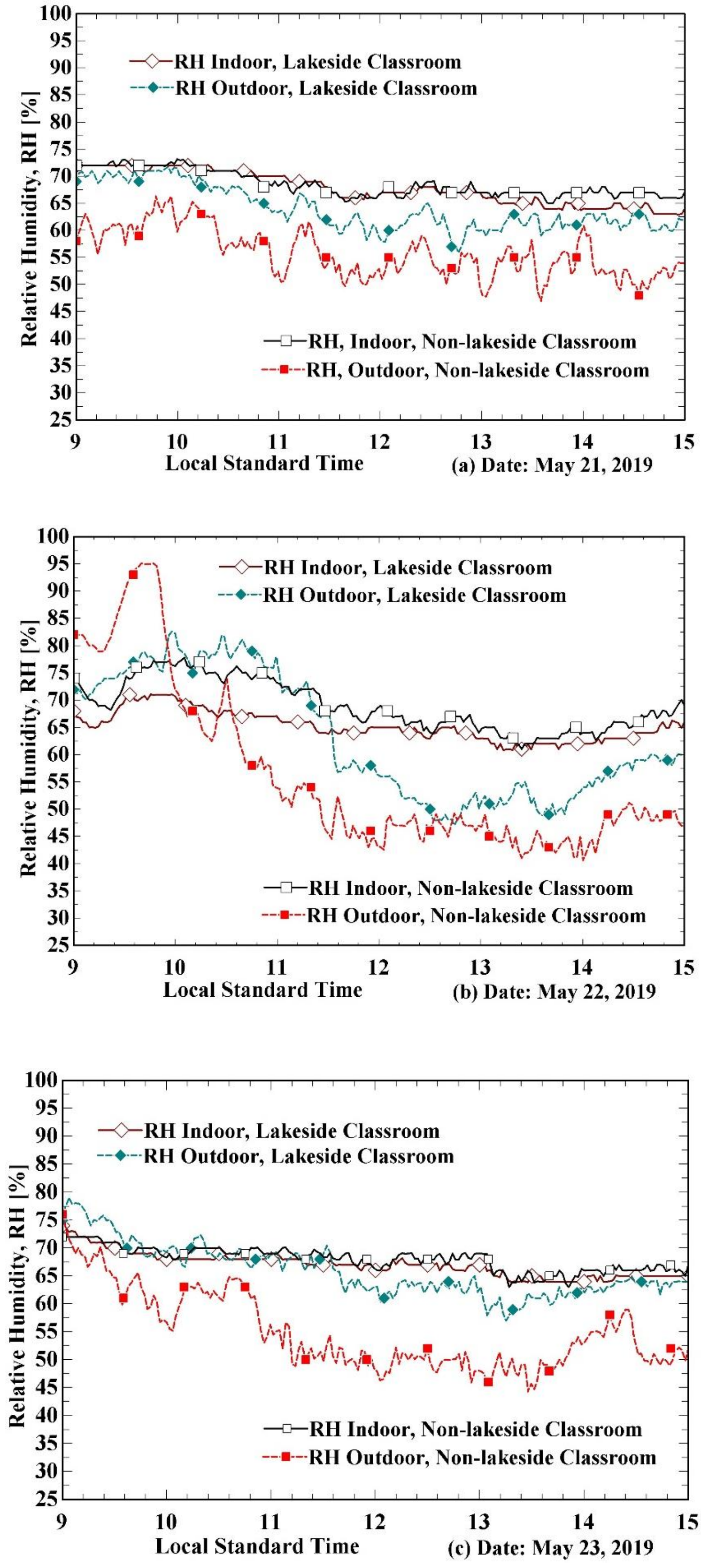


Figure 4.8 Diurnal Distribution of Indoor and Outdoor Relative Humidity of Case 3

The indoor relative humidity (RH_i) of Lakeside Classroom formed comparatively stable (Figure 4.8) trend lines on May 21 and 23. The highest RH_i was found as 74%, with the corresponding T_{ai} of 29°C on May 23. While on May 21, 73% RH_i was recorded with the corresponding T_{ai} of 31.8°C. The lowest RH_i was found as 61% during the afternoon session on May 22. The RH_i was started to rise around 9:21 to 9:35 LST, remained stable up to 10:00 LST, and then dropped steadily up to 14:00 LST the T_{ai} started to fall between 9:21 and 9:35 LST, approaches evenly up to 10:00 LST, and increased steadily. Both the T_{ai} and RH_i formed a more consistent trend on May 23 compared to other measurement dates. The outdoor relative humidity (RH_o) was found lower than RH_i entire of the measurement period on May 21. Higher RH_o values were observed up to 11:00 LST on May 22, when the highest RH_o was recorded as 84%. The RH_o started to drop sharply after 11:00 LST when the lowest value of RH_o was found as 47%. A climbing trend of the T_{ao} was observed at the same time. On May 23, the RH_o was higher than RH_i up to 10:00 LST, remain similar until 11:27 LST, and then dropped.

The air velocity inside Classroom A was higher on May 22, followed by May 23 (Table 4.3). The maximum air velocity was measured as 1.24 ms^{-1} with an average value of 0.04 ms^{-1} on May 22. Ceiling fans were in operation from 12:07 to 12:23 LST on May 23 when the highest air velocity was recorded as 0.68 ms^{-1}. Apart from this, ceiling fans were switched off in all the measurement periods. The doors and windows were open. Compared to other measurement dates, the air velocity outside Classroom C was marginally higher on May 22. The maximum air velocity was found as 3.23 ms^{-1} with an average of 0.73 ms^{-1} on that date. A similar average outdoor air velocity was determined on May 21 and 23. However, the maximum outdoor air velocity was measured as 1.92 ms^{-1} on May 21 and 2.92 ms^{-1} on May 23.

Table 4.3 Indoor and Outdoor Air Velocity, Lakeside and Non-lakeside Classroom

Date	**Average Indoor Air Velocity [ms^{-1}]**		**Average Outdoor Air Velocity [ms^{-1}]**	
	Lakeside Classroom	Non-lakeside Classroom	Lakeside	Non-lakeside
May 21	0.00	0.00	0.50	0.70
May 22	0.04	0.18	0.70	0.70
May 23	0.00	0.06	0.50	0.60

4.3.2. Weather Parameters for Non-lakeside Classroom

Higher T_{ai} was observed in Non-lakeside Classroom on May 21. The maximum T_{ai} was measured as 33.3°C with an average of 32.8°C. The Tai remains lower up to 11:00 LST on May

22 when the minimum T_{ai} was recorded as 27.6°C. Compared to other dates, the T_{ai} trend was found more stable throughout the entire measurement period on May 23. The overall T_{ao} was higher on May 21 (mean T_{ao} 37.7°C) and May 22 (mean T_{ao} 35.5°C). The highest T_{ao} was measured as 41.7°C on May 22 and 40.5°C on May 21. The lowest T_{ao} was found at 24.2°C during the morning session on May 22 because of cloudy weather.

Both RH_i and RH_o were found higher on May 22, followed by May 21. The maximum and the minimum RH_i and RH_o were measured on May 22. The RH_i was higher up to 10:40 LST when the maximum RH_i was found as 78% on that date. Between 9:29 and 9:48 LST, the RHo was found higher with a maximum value of 95%. However, the RH_i and RH_o started to fall as the T_{ai} and T_{ao} commenced to increase with the progress of time. The minimum RH_i and RH_o were recorded as 61% and 40%, respectively. Compared to other dates, the RH_i approached more steadily on May 21.

Unlike Lakeside Classroom, the indoor air velocity was higher on May 22 in Non-lakeside Classroom. The highest air velocity was recorded as 1.34 ms^{-1} with an average of 0.18 ms^{-1}. Ceiling fans were switched off in the classroom during the measurement dates except from 12:44 to 12:55 LST on May 23. The maximum air velocity was measured as 0.58 ms^{-1} with an average of 0.06 ms^{-1}. The average indoor air velocity found comparatively lower on May 21. The mentionable air velocity was measured in the outdoor space of Non-lakeside Classroom (Table 4.3). The average outdoor air velocity of three consecutive measurement dates were 0.70, 0.70, and 0.60 ms^{-1}, respectively. The highest outdoor air velocity was 3.97 ms^{-1} on May 21 and 3.70 ms^{-1} on May 23.

4.4. Case 4: Thermal Environment Comparison between Classrooms with Small Window Area and Large Window Area

The outdoor air temperature and solar irradiation of small window and large window classrooms are illustrated in Figure 4.9. The outdoor air temperature and solar irradiation of large window classroom was higher than the small window classroom. The small window classroom is surrounded by more tree compared to the large window classroom and thus tree influence the air temperature and solar irradiation. On June 15, the outside weather was overcast. Consequently, the outdoor air temperature and solar irradiation were found lower compared to other dates in case of both classrooms.

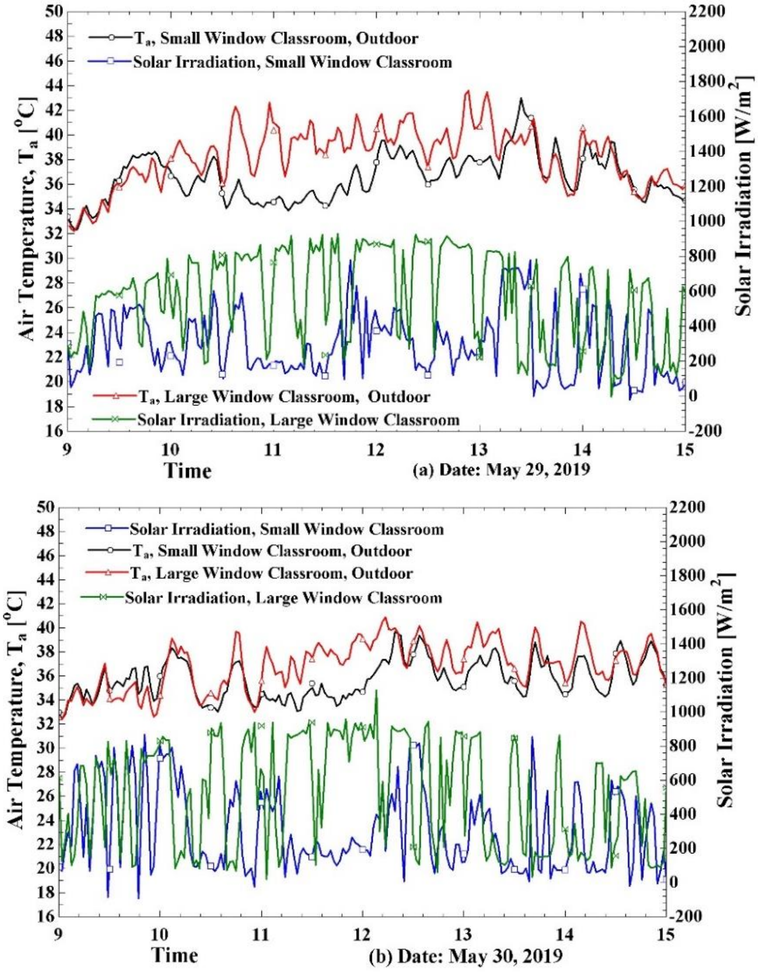


Figure 4.9 Outdoor Air Temperature and Solar Irradiation of Case 4 [Continue in next page]

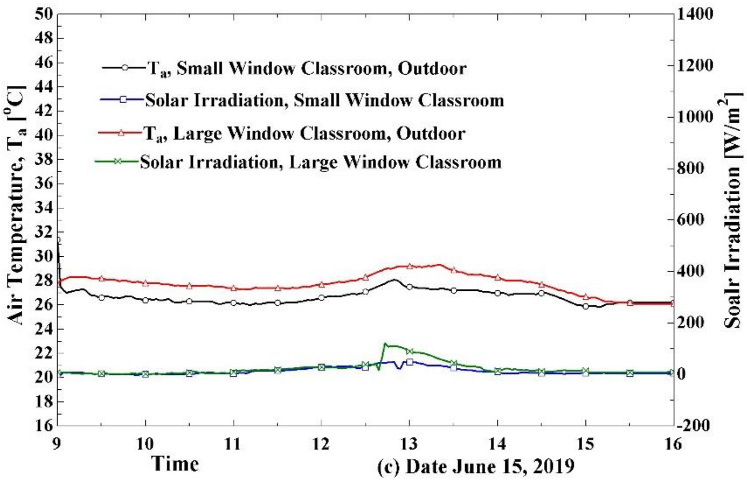


Figure 4.9 Outdoor Air Temperature and Solar Irradiation of Case 4

Figures 4.10 and 4.11 presents the diurnal distribution of indoor and outdoor air temperature, and indoor and outdoor relative humidity, respectively of the classrooms. The indoor air temperature (T_{ai}) found lower than the outdoor air temperature (T_{ao}) on May 29 and 30. However, the T_{ai} was higher than T_{ao} on June 15 because of cloudy weather. The mean T_{ai} of Classroom with Small Window Area and Classroom with Large Window Area were found almost similar during all the measurement dates.

4.4.1 Weather Parameters for the Classroom with Small Window Area

The T_{ai} of Classroom with Small Window approached in a steady way on May 29. The mean T_{ai} was 32.2°C on that date with the highest T_{ai} of 33.1°C. On May 30, the T_{ai} gradually progressed up to 12:30 LST and then started to fall slightly until 15:00 LST. The mean air temperature was 32.3°C on May 30 with the highest T_{ai} of 32.8°C. On June 15, the mean T_{ai} was 28.1°C which was lower compared to other measurement dates. On that date, the T_{ai} was started to drop around 2:35 LST, when the lowest Tai was recorded as 27.1°C. The highest T_{ai} was recorded as 28.8°C in Classroom with Small Window area on June 15. The outdoor air temperature (T_{ao}) of Classroom with Small Window Area was found lower than the Classroom with Large Window Area during all the measurement dates. The mean T_{ao} was 36.6°C on May 29 and 35.7°C on May 30. The highest T_{ao} was recorded as 43°C on May 29 and 39.7°C on May 30. The T_{ao} found lower on June 15 when the lowest T_{ao} was recorded as 25.8°C around Classroom with Small Window Area.

Figure 4.11 presents the diurnal distribution of relative humidity. The Indoor Relative Humidity (RH_i) was found higher in the morning period and started to drop as the air temperature tended to increase with the progress of the time (Figure 4.11) on May 29 and 30.

On June 15, the mean RH_i was 83.9% when the highest RH_i was recorded as 90%. The minimum RH_i was 79% in the same date. The mean RH_i was 71.4% on May 30, and 73.9% on May 29. The minimum RH_i was measured as 68% on May 30, followed by 69% on May 29.

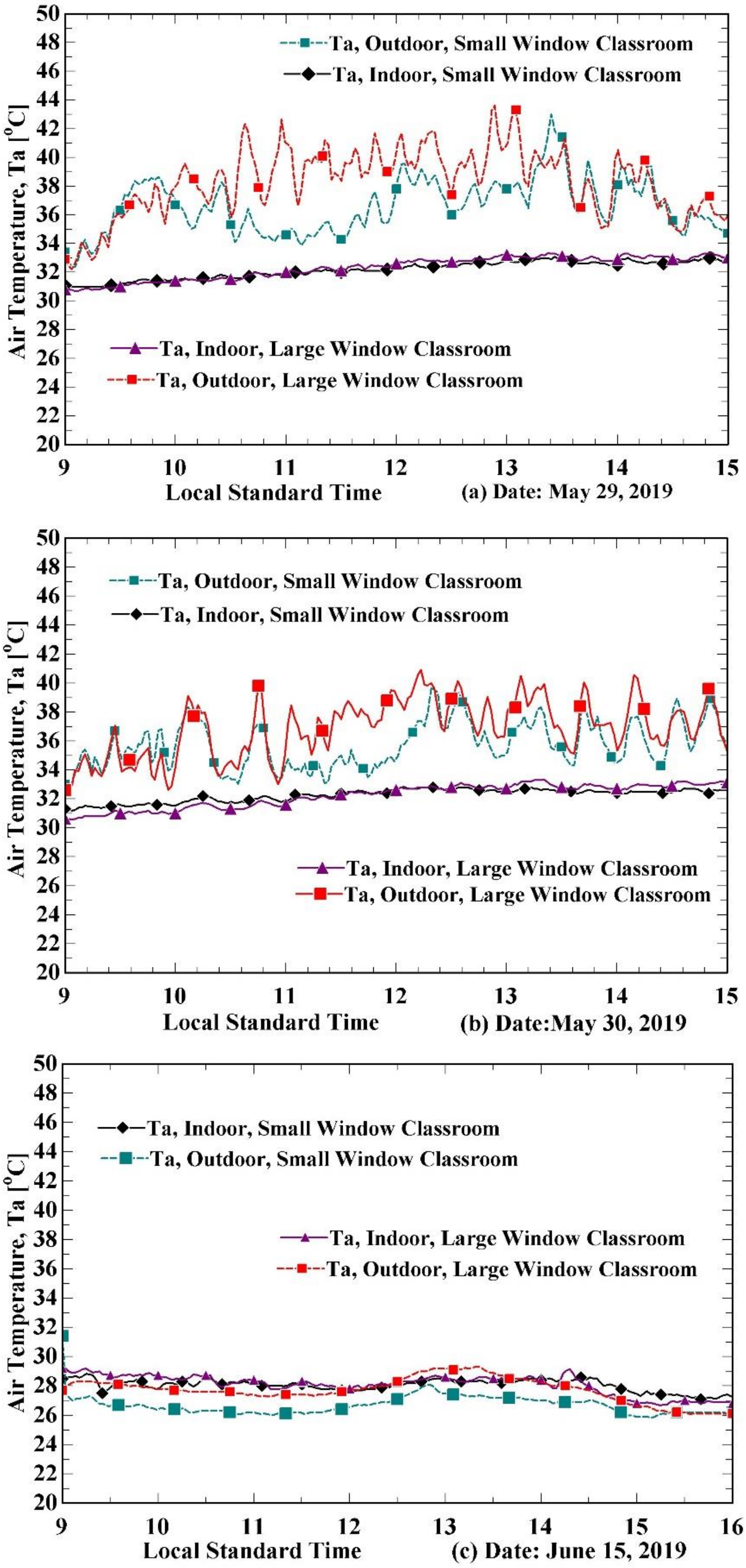


Figure 4.10 Diurnal Distribution of Indoor and Outdoor Air Temperature of Case 4

Apart from June 15, the Outdoor Relative Humidity (RH_o) was found lower than indoor. The RH_o was higher than RH_i on that date. The mean RH_o was 61.3% on May 29 and 61.4% on May 30. The lowest RH_o was measured as 46% on May 29, followed by 51% on May 30. On June 15, in response to lower outdoor air temperature the RH_o was observed higher and relatively stable compared to other measurement dates. The maximum RH_o was measured as 97% with a mean of 92.1% on that date.

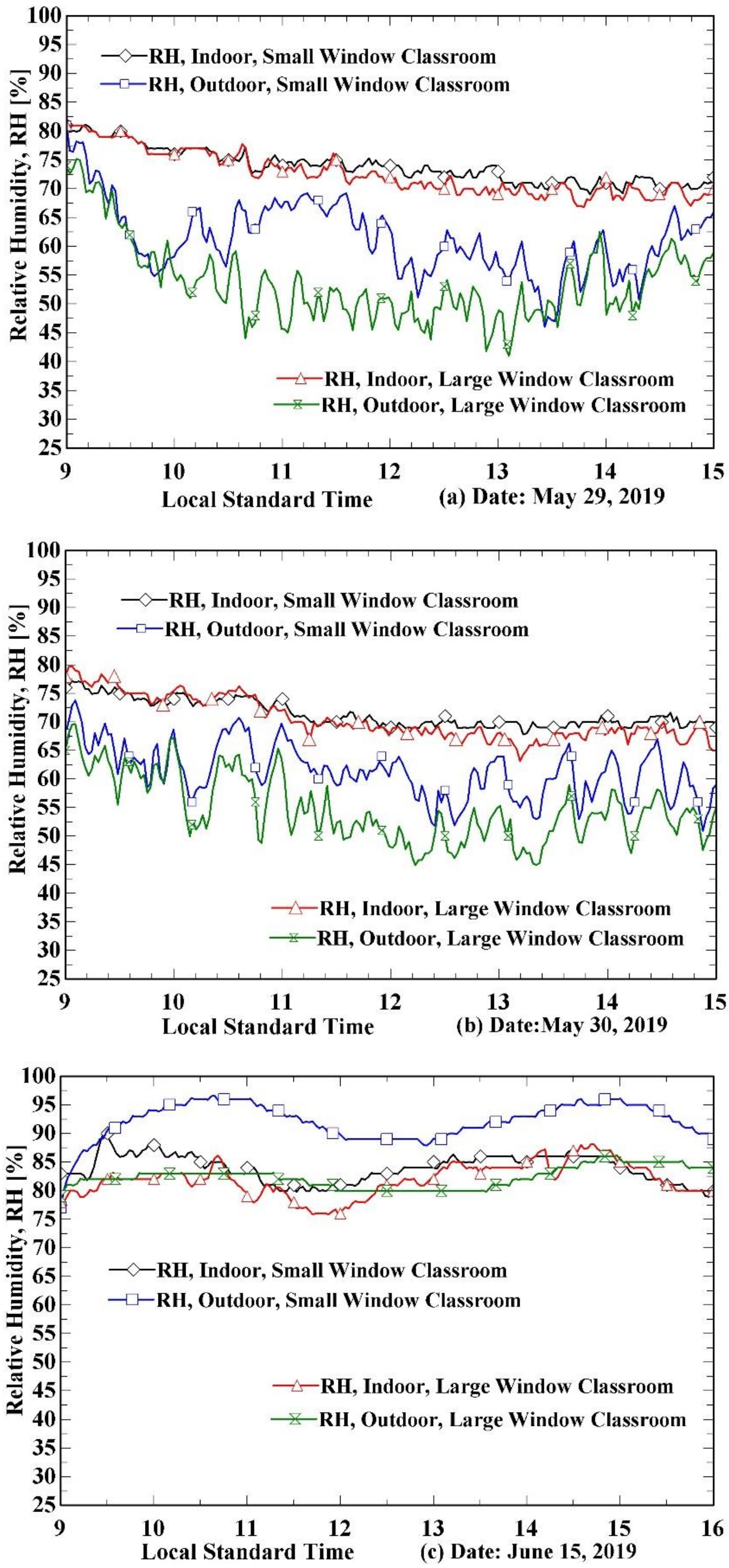


Figure 4.11 Diurnal Distribution of Indoor and Outdoor Relative Humidity of Case 4

Table 4.4 presents the indoor and outdoor air velocity of the classrooms. Inside the Classroom with Small Window Area, the highest air velocity was recorded as 1.25 ms^{-1} with a mean value of 0.06 ms^{-1} on May 30. The lowest air velocity was recorded as 0.22 ms^{-1} on May 29. On June 15, ceiling fans were in operation between 14:20 and 14:40 LST. During that period, the highest air velocity was found 0.48 ms^{-1}. The mean outdoor air velocities of the classrooms were found quite similar during the measurement dates (Table 4.4). The mean outdoor air velocity was determined as 0.50 ms^{-1} on May 29. On that date, the highest outdoor air velocity was recorded as 2.28 ms^{-1}. On May 30, the mean outdoor air velocity was 0.40 ms^{-1}. The maximum outdoor air velocity was recorded as 2.26 ms^{-1} on May 30. The mean outdoor air velocity was found same (0.20 ms^{-1}) for both the classrooms on June 15. The highest outdoor air velocity was found as 1.78 ms^{-1} on that date.

4.4.2 Weather Parameters for the Classroom with Large Window Area

For the Classroom with Large Window Area, the indoor air temperature (T_{ai}) formed a steady increased trend on May 29. The mean T_{ai} was 32.3°C on May 29 and 32.2°C on May 30. The highest T_{ai} was recorded as 33.4°C on May 29, followed by 33.3°C on May 30. The mean air temperature was 32.2°C on May 30 with a highest T_{ai} of 33.3°C. The mean T_{ai} was 28.1°C on June 15, which was lower compared to other measurement dates. On June 15, the T_{ai} was started to drop around 2:35 LST. On that period, the lowest T_{ai} was recorded as 26.7°C. The highest T_{ai} was recorded as 29.2°C on June 15. The outdoor air temperature (T_{ao}) of Classroom with Large Window Area was found higher than Classroom with Small Window Area during all the measurement dates. The mean T_{ao} was determined as 38.3°C on May 29 and 36.9°C on May 30. The highest T_{ao} was recorded as 43.8°C on May 29, followed by 41.1°C on May 30. The T_{ao} found lower on June 15 when the lowest T_{ao} was recorded as 26.1°C with a mean value of 27.7°C.

Table 4.4 Indoor and Outdoor Air Velocity, Small and Large Window Classroom

Date	**Average Indoor Air Velocity [ms^{-1}]** Small Window Classroom	Large Window Classroom	**Average Outdoor Air Velocity [ms^{-1}]** Small Window	Large Window
May 29	0.00	0.43	0.50	0.40
May 30	0.06	0.44	0.40	0.54
June 15	0.00	0.00	0.20	0.20

The Indoor Relative Humidity (RH_i) was found higher in the morning period and started to drop as the air temperature tended to increase with the progress of the time on May 29 and 30. The RH_i of the classrooms remained similar up to around 10:50 LST on May 29 and 11:00

LST on May 30. The mean RH_i was 70.5% on May 30 and 72.6% on May 29. The minimum RH_i was measured as 63% on May 30, and 67% on May 29. Compared with other measurement dates, the RH_i was higher on June 15. On that date, the mean RH_i was calculated as 81.9% with the highest RH_i was recorded as 88%. The Outdoor Relative Humidity (RH_o) was found lower than its indoor counterpart apart from June 15. The mean RH_o was 53.7% on May 29, and 54.7% on May 30. Hence, the minimum RH_o was measured as 41% on May 29 and 45% on May 30. On June 15, the RH_o was observed higher and relatively stable compared to other measurement dates. The maximum RH_o was recorded as 86% with a mean value of 83.2% on that date.

The air velocity inside the Classroom with Large Window Area was higher (Table 4.4) than the Classroom with Small Window Area on May 29 and 30. The highest air velocity was recorded as 1.96 ms^{-1} inside the Classroom with Large Window Area on May 30 with a mean value of 0.44 ms^{-1}. On May 29, the maximum air velocity was recorded as 1.87 ms^{-1} with a mean value of 0.44 ms^{-1}. The mean air velocity was 0.2 ms^{-1} on June 15. Ceiling fans were switched on between 14:10 and 14:21 LST on June 15 and thereby the maximum air velocity was measured as 0.77 ms^{-1} on that period. The mean outdoor air velocity was 0.40 ms^{-1} on May 29 with a highest value recorded as 2.27 ms^{-1}. On May 30, the mean air velocity was 0.54 ms^{-1} with a maximum value recorded as 3.13 ms^{-1}. The mean outdoor air velocity was found same (0.20 ms^{-1}) for both the classrooms on June 15. The highest air velocity was found as 1.83 ms^{-1} outside of the Classroom with Large Window Area on that date. The weather was overcast on June 15 and the air remained almost still until around 12:50 LST. Though the outdoor air velocity were similar for both classrooms, the indoor air velocity of large window classroom was found higher than small window classroom A. Larger window area (17.3 m^2) of that classroom stimulate the air velocity.

4.5. Case 5: Thermal Environment Analysis of Studio Type Classroom

Diurnal distribution of indoor and outdoor air temperature and relative humidity in different days are presented in Figure 4.12. Outdoor air temperature (T_{ao}) found higher than indoor air temperature (T_{ai}) during the measurement periods. A steady increase in T_{ai} is observed while T_{ao} advances with a fluctuation rate. T_{ai} and T_{ao} are found lower in the morning and started to rise from the afternoon. Since solar radiation progresses with time, both T_{ai} and T_{ao}, in general, tend to form an increasing trend. T_{ai} possesses a similar type of trend like T_{ao} during the measurement period except up to 11:30 LST on June 13 because of cloudy weather.

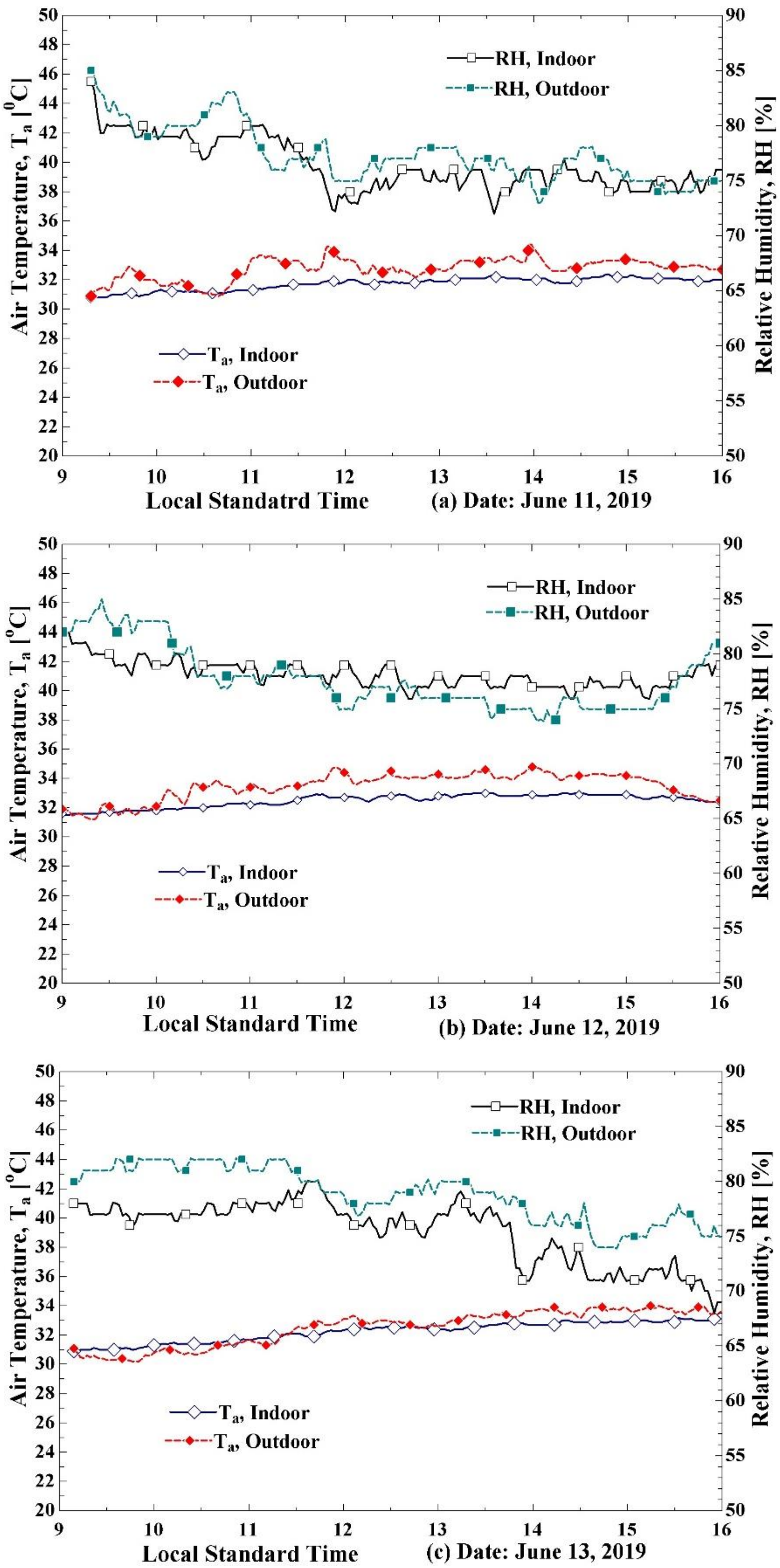


Figure 4.12 Diurnal Distribution of Indoor and Outdoor Air Temperature and Relative Humidity of Case 5

The values of relative humidity inside the classroom (RH_i) were lower than in outdoor space on June 11 and 13. On June 12, outdoor relative humidity (RH_o,) started to fall from 12:00 to 15:00 LST as outdoor temperature increased and tended to rise from 15:30 LST as the temperature started to decrease. Both the values of RH_i and RH_o were higher in the morning and started to decrease as air temperature increased with the progress of time. A decreasing tendency of both RH_i and RH_o was observed from 12:00 LST when air temperature also tends to increase.

Table 4.5 Indoor and Outdoor Air Velocity, Studio Type Classroom

Date	**Indoor Air Velocity [ms^{-1}]**			**Outdoor Air Velocity [ms^{-1}]**		
	Maximum	Minimum	Average	Maximum	Minimum	Average
June 11	0.00	0.00	0.00	1.17	0.00	0.07
June 12	0.00	0.00	0.00	0.93	0.00	0.00
June 13	1.11	0.00	0.00	1.29	0.00	0.26

Measured indoor and outdoor air velocity is presented in Table 4.5. The outdoor air velocity was higher than the indoor counterpart. The maximum air velocity (1.11 ms^{-1}) was recorded in the classroom on June 13 when ceiling fans were in operation from 11:38 to 11:51 LST. Ceiling fans were not operated apart from this period, and air remained still inside the classroom. Door and windows of the classroom were open during the field measurement period. The outdoor air velocity change more frequently than indoor. The maximum fluctuation rate of air velocity was observed on June 13, followed by June 11. On June 13, the maximum outdoor air velocity was measured at 1.29 ms^{-1}, with the highest average of 0.26 ms^{-1}. However, the changing pattern of air velocity found steady on June 12 as compared to other measurement days.

4.6. Case 6: Thermal Environment Analysis of Seminar Library

The outdoor air temperature and solar irradiation are plotted in Figure 4.13. The outdoor air temperature seems correspondence to the solar irradiation during the measurement dates.

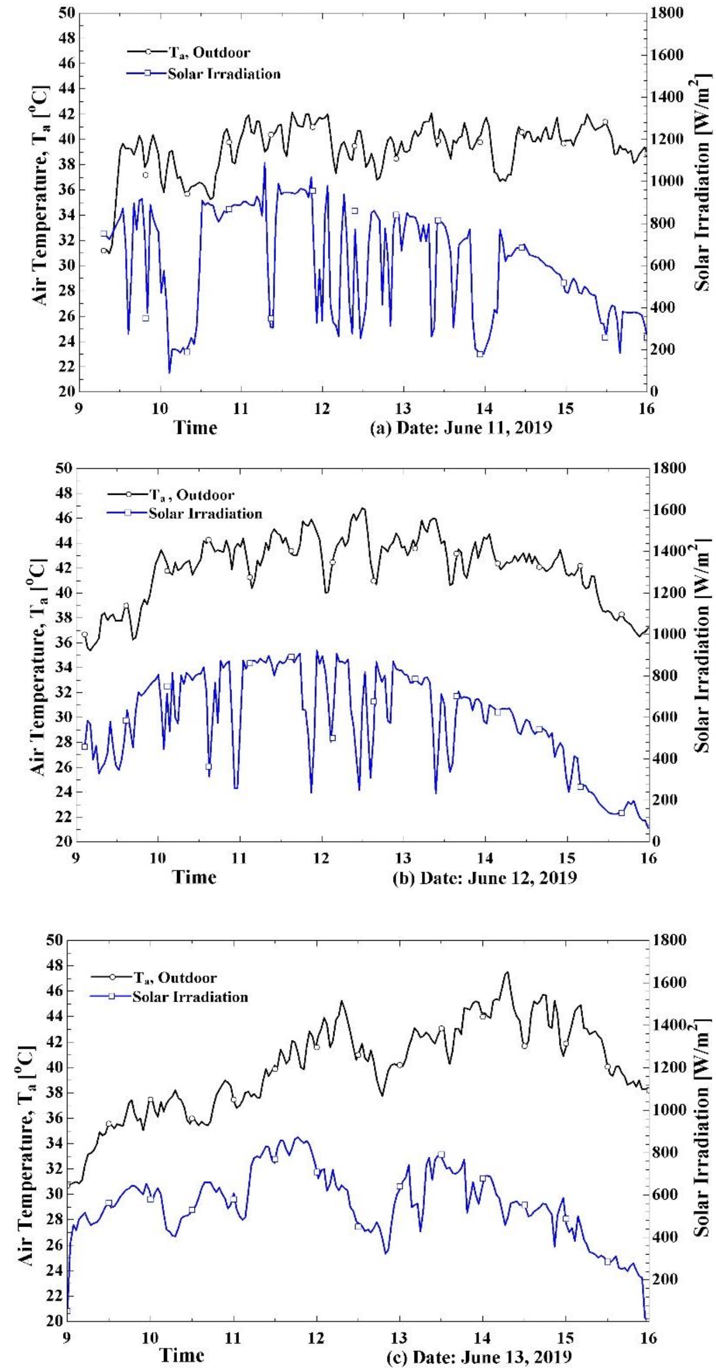


Figure 4.13 Outdoor Air Temperature and Solar Irradiation of Case 6

Figure 4.14 illustrates the diurnal distribution of indoor and outdoor air temperature and relative humidity of the Seminar Library. The Indoor Air Temperature (T_{ai}) and Relative Humidity (RH_i) were found more stable than the Outdoor Air Temperature (T_{ao}) and Relative Humidity (RH_o). The T_{ai} was recorded lower than T_{ao}, while the RH_i was higher than RH_o during the measurement dates.

The T_{ai} found lower in the morning period and started to increase steadily with the progress of time. The highest mean T_{ai} was determined as 33.3^oC on June 12. The maximum T_{ai} was recorded as 34.4^oC on June 12 followed by 34.1^oC on June 13. Due to the overcast condition, the T_{ai} was lower up to 10:10 LST on June 13. During this period, the minimum T_{ai} was recorded as 30.6^oC. The mean T_{ao} were calculated as 39.3^oC in June 11, 42^oC on June 12, and 40.1^oC on June 13. However, the highest T_{ao} was recorded as 47.6^oC on June 13 and 47^oC on June 12. The lowest T_{ao} was found as 30.7^oC on June 13, and 31^oC on June 11.

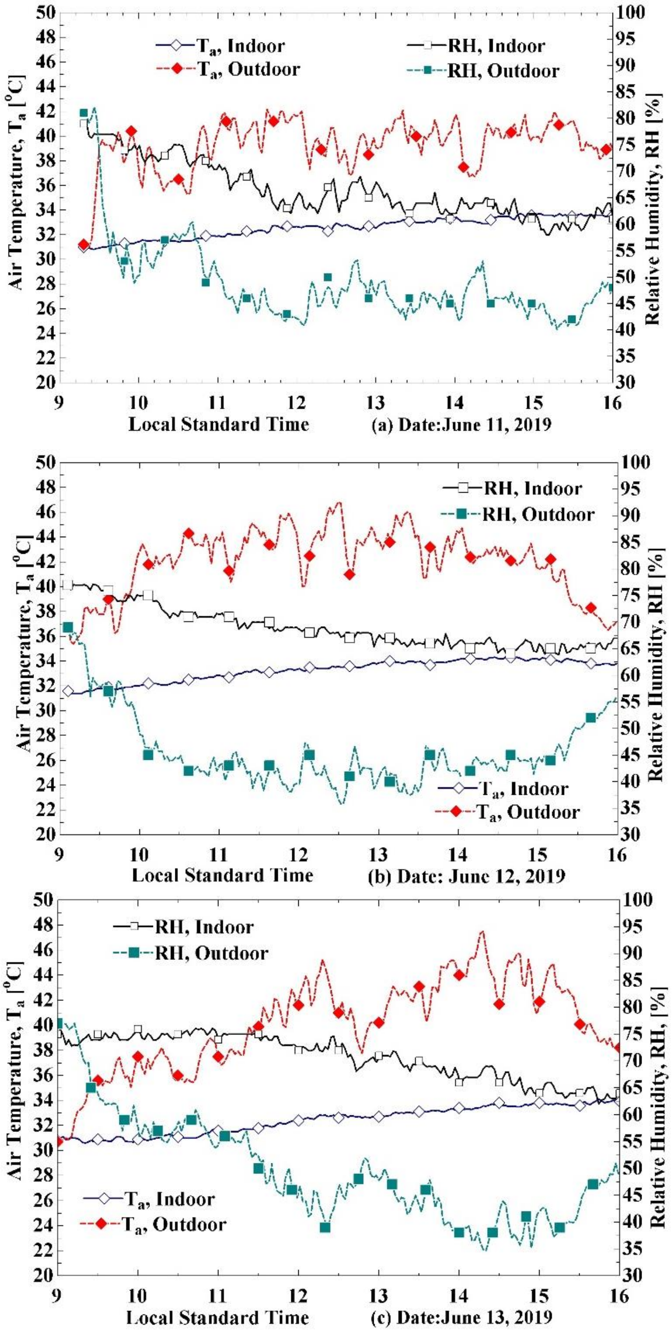


Figure 4.14 Diurnal Distribution of Indoor and Outdoor Air Temperature and Relative Humidity of Case 6

Both the RH_i and RH_o were found higher in the morning period and tend to decrease as the air temperature started to increase. The mean RH_i were as 66.5% on June 11, 68.9% on June 12, and 70.7% on June 13. The maximum RH_i were recorded as 80% on June 11 and 77% on June 13. While the minimum RH_i were found as 57% on June 11 and 62% on June 13. In response to higher T_{ao}, the lowest mean RH_o was 45.6% on June 12. The minimum RH_o was recorded as 33% with T_{ao} of 46.3 on June 13 and 35% with T_{ao} of 45.5°C on June 12. The highest mean RH_o was 49.6% on June 13 followed by 48.8% on June 11. The maximum RH_o was recorded as 82% on June 11 and 77% on June 12 when the air temperature was lower at the morning period.

Table 4.6 Indoor and Outdoor Air Velocity, Seminar Library

Date	**Indoor Air Velocity [ms^{-1}]**			**Outdoor Air Velocity [ms^{-1}]**		
	Maximum	Minimum	Average	Maximum	Minimum	Average
June 11	1.67	0.00	0.30	1.85	0.00	0.30
June 12	1.43	0.00	0.21	1.93	0.00	0.40
June 13	0.77	0.00	0.06	2.32	0.00	0.53

Measured indoor and outdoor air velocity is presented in Table 4.6. Windows and doors were remained open during the measurement dates. Ceiling fans were in operation on June 11, between 9:10 and 13:03 LST on June 12, and between 12:21 to 12:39 LST on June 13. Therefore, the mean indoor and outdoor air velocity were found similar (0.30 ms^{-1}) on June 11. The indoor air velocity fluctuated more on June 11 compared to other measurement dates. The maximum indoor air velocity was recorded as 1.67 ms^{-1} on June 11 and 1.43 ms^{-1} on June 12. The outdoor air velocity was higher than the indoor counterpart on June 12 and 13. The mean outdoor air velocity was determined higher (0.53 ms^{-1}) on June 13 and lower (0.30 ms^{-1}) on June 11. The maximum outdoor air velocity was recorded as 2.32 ms^{-1} on June 13 and 1.93 ms^{-1} on June 12.

4.7 Conclusion

The field measurement was carried out in the typical hot summer days between May and June in different indoor and outdoor university spaces. The filed measurement results indicate that the indoor weather parameters approach in a steady manner as the time progresses. The outdoor weather parameters, on contrary, fluctuated in a greater extent. The outdoor air temperature and air velocity were recorded higher than their indoor counterparts. Both the indoor and outdoor air temperature were found low in the morning and steadily increased with the progress of time. The relative humidity formed a reverse trend with the increase of air temperature.

Classrooms located in different floors of a building possess different indoor air temperature. The air temperature of 1st and 2nd floor classrooms were lower compared to the 3rd floor classroom of a three-storied building. The top floor gains more heat through the roof as well as windows and exterior wall. The air temperature inside large window area classroom was slightly higher than the small window classroom. Larger window allowed more solar irradiation and thus the air temperature became higher.

The indoor thermal environments correspond to those surrounding outdoor weather. For example, the outdoor air temperature of more tree area was found lower than the outdoor air temperature of area with less tree. In response to the outdoor condition, air temperature in the classroom surrounded by more tree area was also found lower than in the classroom surrounded by less tree area. Similar measurement was carried out to detect the air temperature difference in lakeside and non-lakeside classrooms. The outdoor air temperature near the lakeside classroom was found lower than the outdoor air temperature near non-lakeside classroom. However, the indoor air temperature of the lakeside classroom was found slightly higher than non-lakeside classroom. The lakeside classroom is located on the top floor of the building and exposed more to the sunlight and thus slightly increased air temperature was found. The non-lakeside classroom, on the other hand, is not located on the top floor and exposed less to the sunlight and thereby less affected by solar irradiation.

Chapter 5

Evaluation of Thermal Comfort in Indoor and Outdoor University Spaces

Standard Effective Temperature (SET*) is being widely used to evaluate the thermal comfort condition as this index combined both weather factors and human factors effectively. SET* has been calculated for different university spaces as described in Chapter 3. Thermal comfort condition of different indoor and outdoor university spaces will be evaluated through SET* in this chapter.

5.1 Case 1: Thermal Comfort Comparison among the Classrooms Located in Different Floors of the Same Building

Calculated values of the Standard Effective Temperature (SET*) in different measurement dates are plotted in the Figure 5.1.

5.1.1 Indoor Thermal Comfort Analysis of Case 1

Larger window area of 1st floor Classroom allows more air circulation which resulted more fluctuation in the SET* values inside 1st floor Classroom compared to the other classrooms. The SET* values were within the standard comfort zone on May 25 with a minimum value of 23.4^{o}C (‘Comfortable’ sensation). On May 28, the minimum SET* value was calculated as 27.9^{o}C with ‘Slightly Warm’ sensation. While the maximum SET* value was 36.4^{o}C on May 27 and 35.4^{o}C on May 28 with ‘Hot’ sensation inside 1st floor Classroom. In 2nd floor Classroom, the minimum SET* value was calculated as 26.7^{o}C on May 25 and 29.4^{o}C on May 26 with ‘Slightly Warm’ sensation. The maximum SET* was 34.9^{o}C on May 27 and 34.7^{o}C on May 28 with ‘Hot’ sensation in that classroom. Being located on the top floor, the 3rd floor Classroom was exposed more to the direct solar heat gain. Consequently, the SET* values were found higher than other classrooms. The minimum SET* value was 27.3^{o}C with ‘Slightly Warm’ sensation on May 25. The maximum SET* value was calculated as 36.8^{o}C on May 27 and 36.6^{o}C on May 28 with “Hot” sensation.

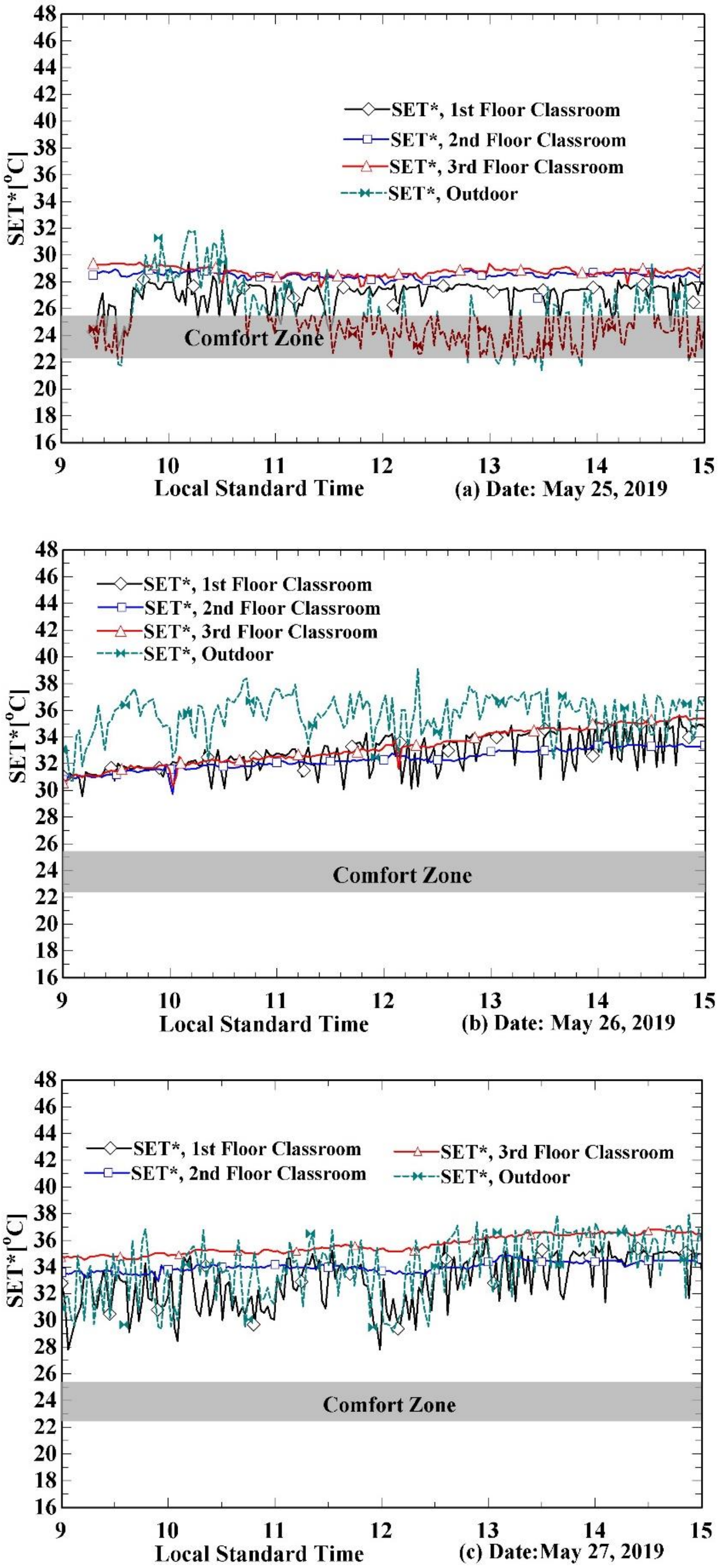


Figure 5.1 Indoor and Outdoor SET* Trend in Different Floor Classrooms [Continue in next Page]

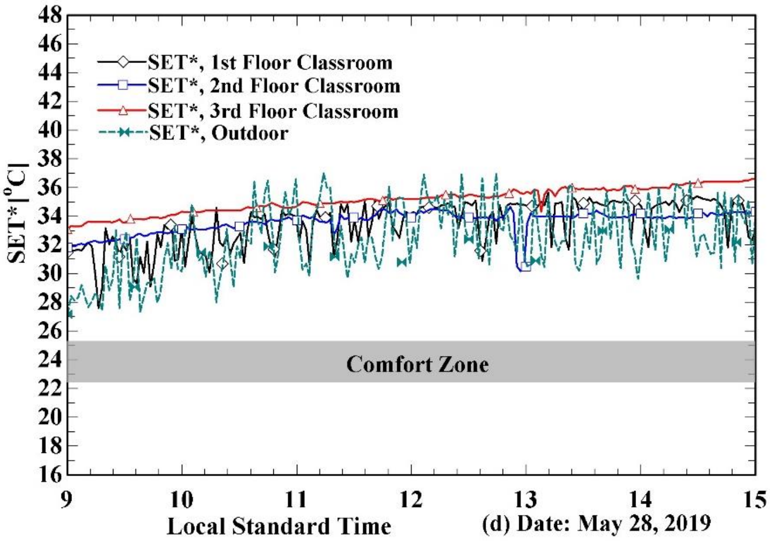


Figure 5.1 Indoor and Outdoor SET* Trend in Different Floor Classrooms

The SET* values were dropped between 12:35 and 12:45 LST in 1st floor, 12:53 and 13:00 LST in 2nd floor, and 13:08 and 13:18 LST in 3rd floor classrooms on May 28 when ceiling fans were switched on. During those periods, the minimum SET* was 30.9°C in 1st floor Classroom, 30.2°C in 2nd floor Classroom, and 33.1°C in 3rd floor Classroom with 'Warm' sensation.

5.1.2 Outdoor Thermal Comfort Analysis of Case 1

The outdoor SET* values fluctuated more than their indoor counterpart in response to the environmental parameters during all the measurement dates. The mean outdoor SET* values were found lower than indoor SET* values on May 25 and May 28. The minimum outdoor SET* was determined as 21.5°C on May 25 with 'Slightly Cool' sensation and 27.2°C on May 28 with 'Slightly Warm' sensation. The outdoor SET* values were found within the standard comfort zone in most of the time except between 10:00 and 11:00 LST, and 14:00 and 15:00 LST on May 25 because of lower air temperature (27.7°C) and mentionable air velocity (0.86 ms^{-1}). On May 27, the mean outdoor SET* was higher than 1st floor Classroom, similar to the 2nd floor Classroom and lower than 3rd floor Classroom. The mean outdoor SET* values were higher than the mean indoor SET* values of all the classrooms on May 26 because of higher outdoor air temperature. The maximum SET* values were calculated as 39.1°C on May 26 with 'Very Hot' sensation and 37.1°C on May 27 with 'Hot' sensation. Higher air temperature (34.1°C) coupled with lower air velocity (0.14 ms^{-1}) resulted higher outdoor SET* values on May 26. The increased air velocity (0.55 ms^{-1}) kept the mean outdoor SET* values comparatively lower on May 28.

5.2 Case 2: Thermal Comfort Comparison between Classrooms Surrounded by More Tree (1525.3 m^2) and Less Tree (307.5 m^2)

Indoor and outdoor SET* values in different measurement dates are plotted in the Figure 5.2. The SET* values inside classrooms were found more stable than its outdoor counterparts. In response to the frequent change of outdoor environmental parameters, the outdoor SET* values fluctuated in greater extent.

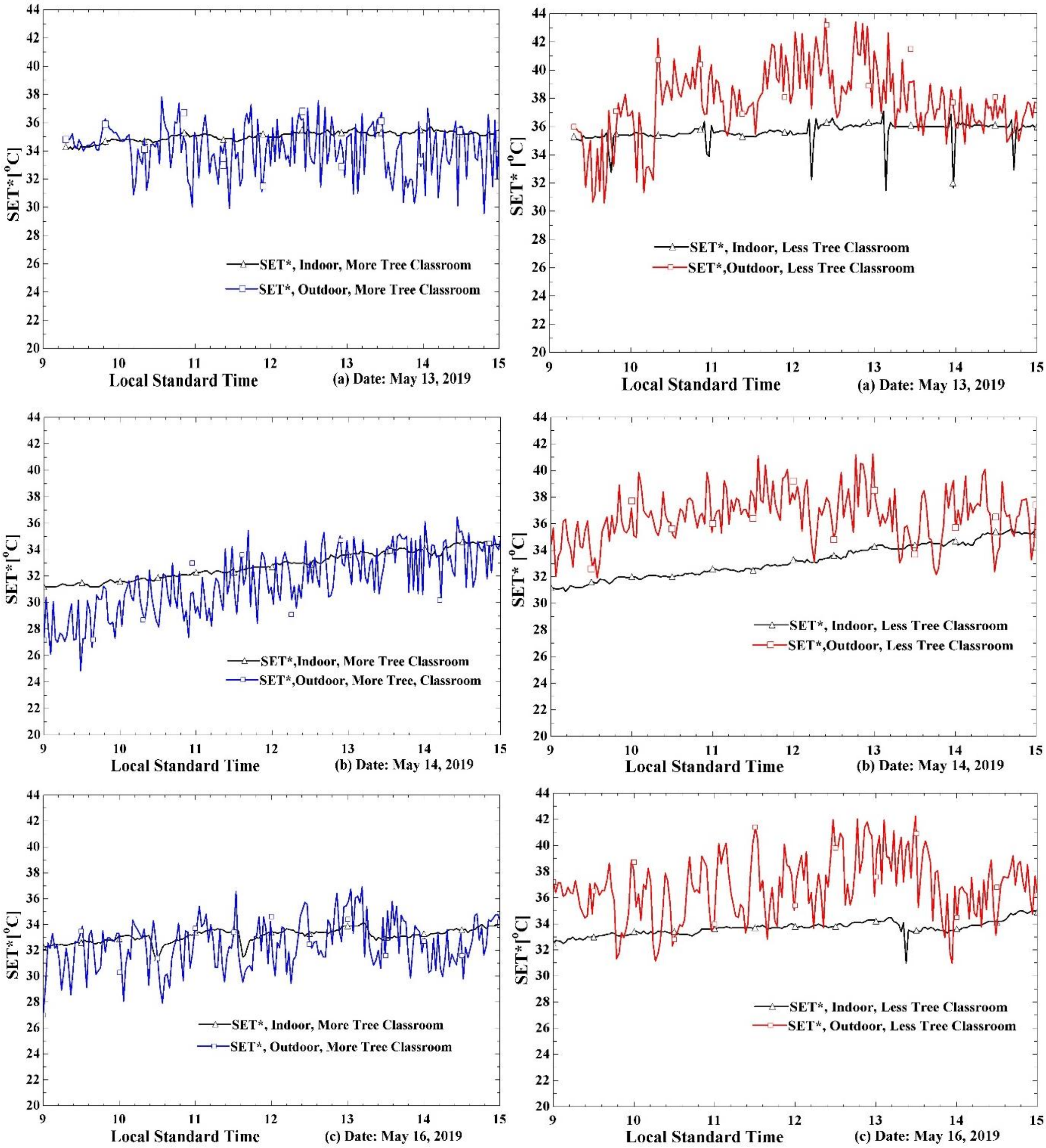


Figure 5.2 Indoor and Outdoor SET* in More Tree and Less Tree Classroom [Continue in next page]

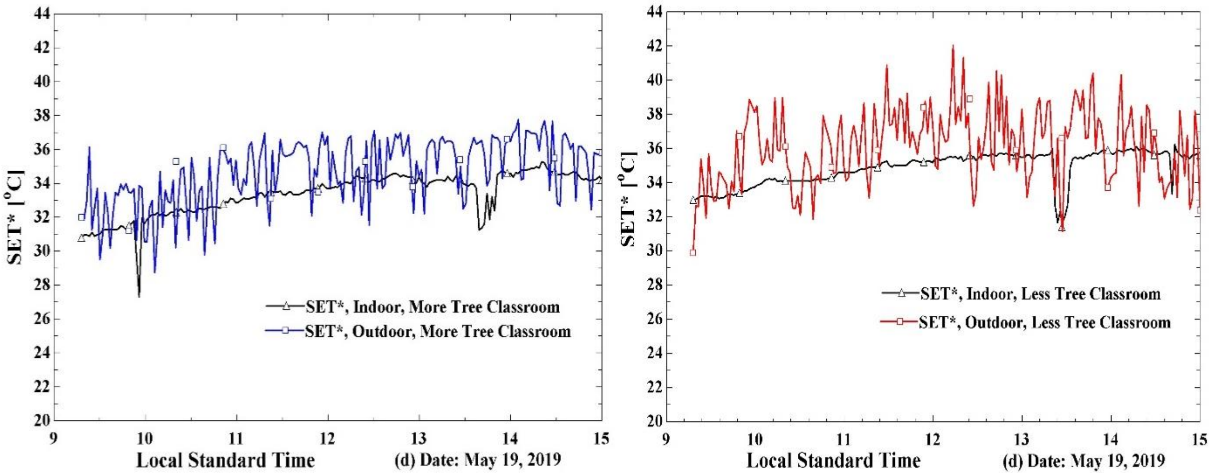


Figure 5.2 Indoor and Outdoor SET* in More Tree and Less Tree Classroom

The calculated outdoor SET* values for Classroom surrounded by Less Tree were much higher than that of indoor in most of the measurement periods (Figure 5.2). Higher outdoor air temperature resulted higher outdoor SET* values for the less tree classroom. In case of Classroom surrounded by More Tree, the outdoor air temperature was lower and consequently the SET* values were found comparatively lower (Figure 5.2). Fluctuation in outdoor SET* trend was resulted from the rapid change in air velocity in case of both classrooms.

5.2.1 Indoor Thermal Comfort Analysis of Case 2

The SET* values were low inside classrooms in the morning and then started to increase steadily in response to the increase in air temperature (Figure 5.3). Higher SET* values were evident in Classroom surrounded by Less Tree during the measurement periods than Classroom surrounded by More Tree. The SET* values of Classroom surrounded by Less Tree were 1.6°C higher than its counterpart Classroom on May 19, followed by 0.7°C on May 13 and 0.6°C in May 16. During these dates, higher air temperature inside Classroom Surrounded by Less Tree yielded higher SET* values than Classroom surrounded by More Tree. On May 14, the indoor SET* values of less tree classroom were 0.4°C higher than more tree classroom. The indoor air temperature of the less tree classroom was slightly higher than the more tree classroom in that day.

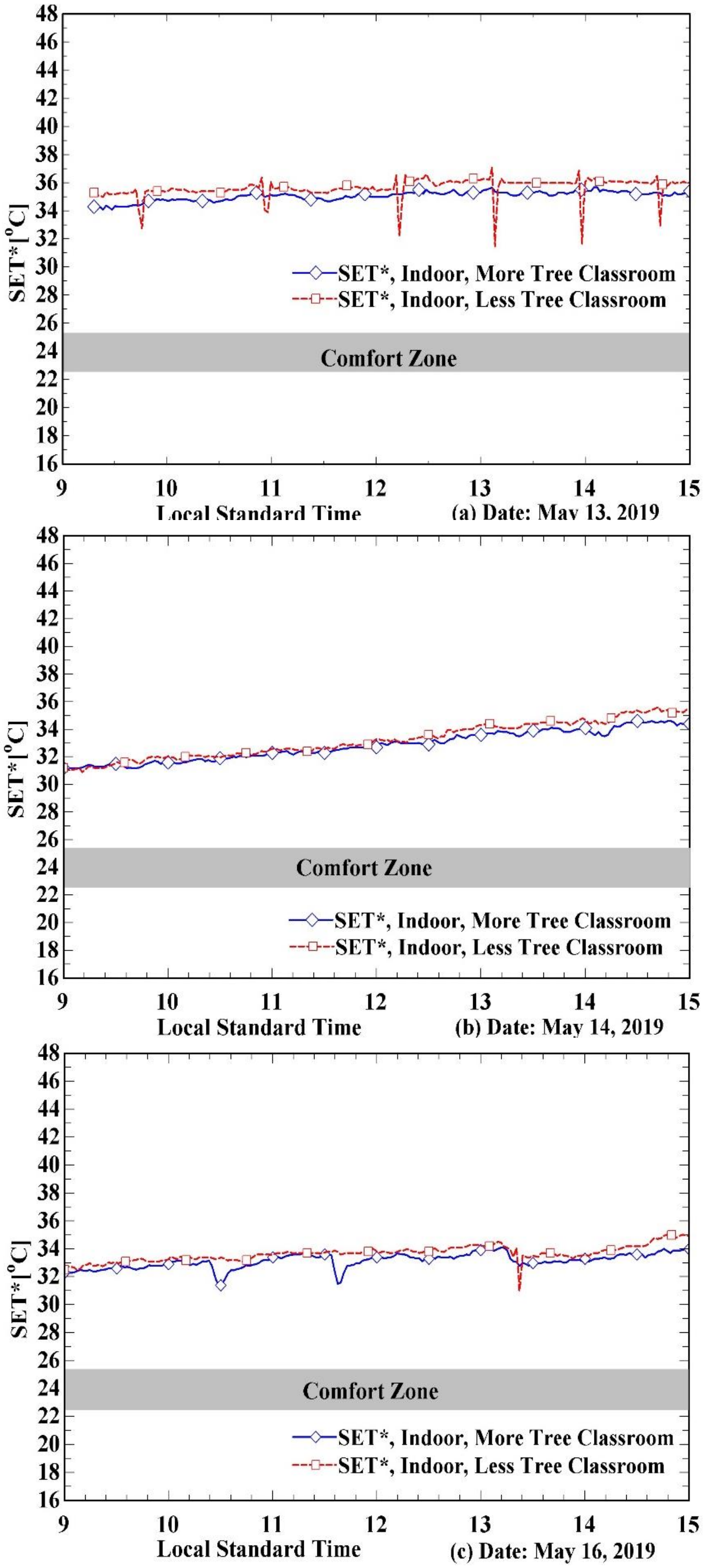


Figure 5.3 Indoor SET* Trend of More Tree and Less Tree Classroom [Continue in next Page]

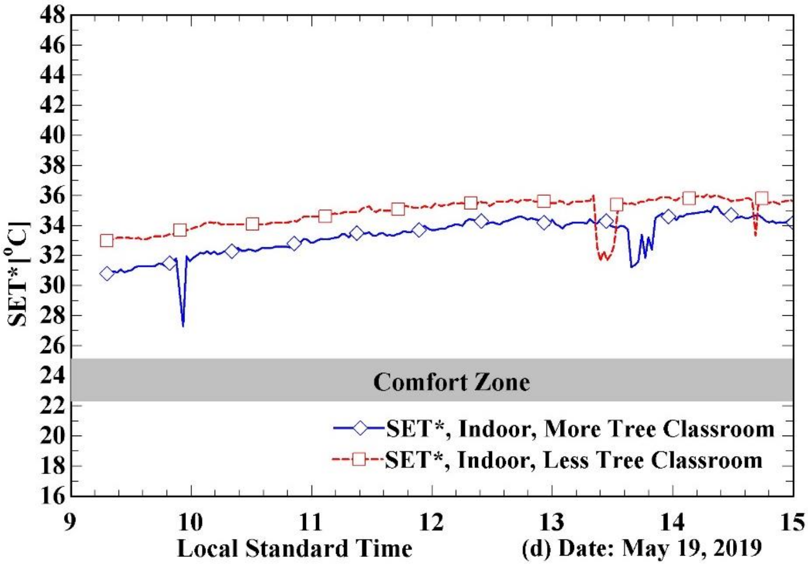


Figure 5.3 Indoor SET* Trend of More Tree and Less Tree Classroom

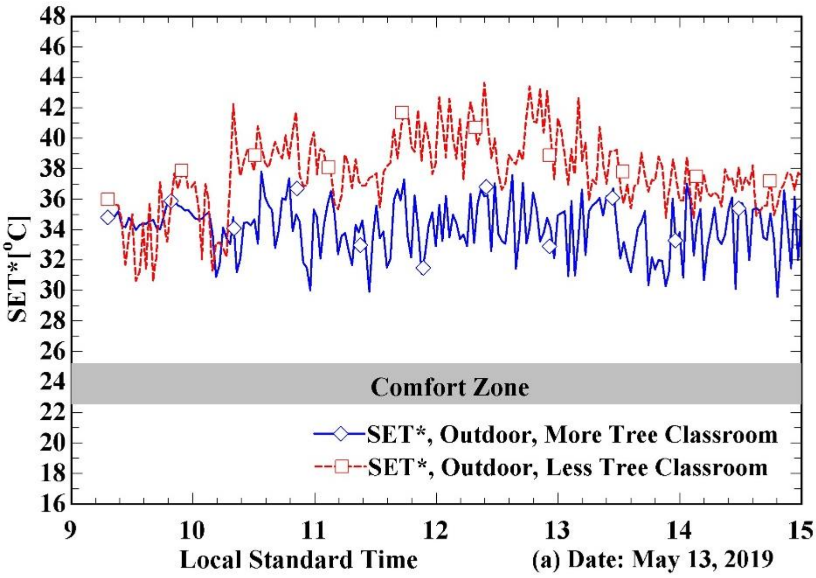
Except some periods on May 16 and 19, the SET* values inside Classroom surrounded by More Tree were away from the ASHREA-17 recommended comfort zone. The highest SET* values were found 35.7^{o}C on May 13 and 35.3^{o}C with 'Hot' sensation on May 19 resulted from higher air temperature and still air. Lower air temperature resulted lower SET* values were on May 16 at 10:29 and 11:21 LST in more tree classroom. On May 19 at 09:56 LST the lowest SET* was evident as 26.3^{o}C with 'Slightly Warm' sensation due to lower air temperature coupled with mentionable wind velocity (1.07ms^{-1}) inside Classroom surrounded by More Tree. Furthermore, ceiling fans were in operation between 13:41 to 13:52 LST. Hence SET* values were also dropped during this period with a minimum value of 31.3^{o}C with 'Warm' sensation.

The average SET* values were higher in Classroom surrounded by Less Tree on May 13 (35.7^{o}C) followed by May 19 (34.9^{o}C). The highest SET* values were calculated as 36.6^{o}C on May 13 and 36.1^{o}C with 'Hot' sensation on May 19 because of higher air temperature. The difference between the indoor SET* values of more tree and less tree classroom was found lower compared to other dates. This situation mainly occurred due to lower indoor air temperature difference between the classrooms. Certain tumble downs were observed other than on May 14. The SET* values dropped at 9:56, 11:05, 12:20, 12:22, 13:12, 14:00, and 14:43 LST on May 13 due to air velocity. Similar situation occurred at 9:47, 10:25, and 13:22 LST on May 16 and 14:42 LST on May 19. The SET* values in Classroom surrounded by Less

Tree were lower from 13:26 to 13:34 LST on May 19. Ceiling fans were in operation during this time and the lowest SET* value was determined as 31.4°C with 'Warm' sensation.

5.2.2 Outdoor Thermal Comfort Analysis of Case 2

The outdoor SET* values of Classroom surrounded by More Tree were found much lower (Figure 5.4) than Classroom surrounded by Less Tree. On average, the outdoor SET* values of Classroom surrounded by More Tree were 5.2°C lower than Classroom surrounded by Less Tree on May 14, followed by 4.2°C on May 16 and 3.8°C on May 13. The classroom which was surrounded by more tree reduced the air temperature by the evapotranspiration process.



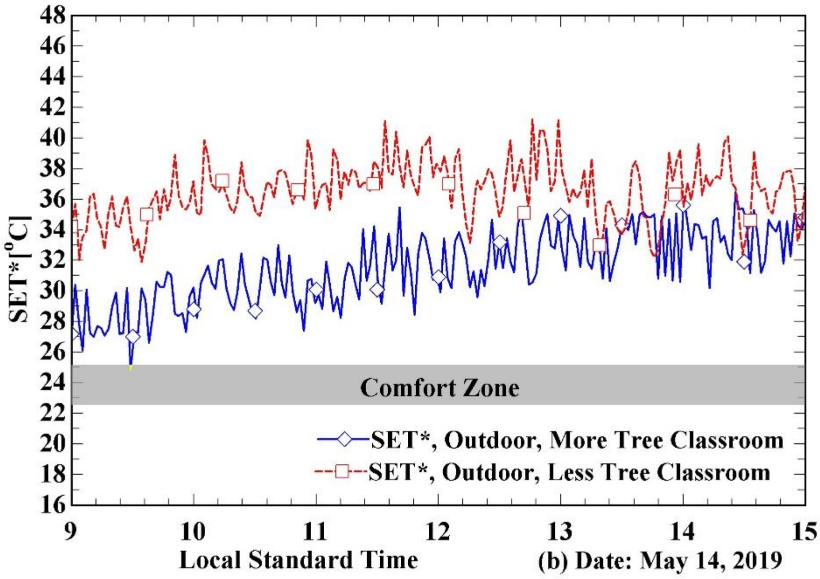


Figure 5.4 Outdoor SET* Trend of More Tree and Less Tree Classroom [Continue in next Page]

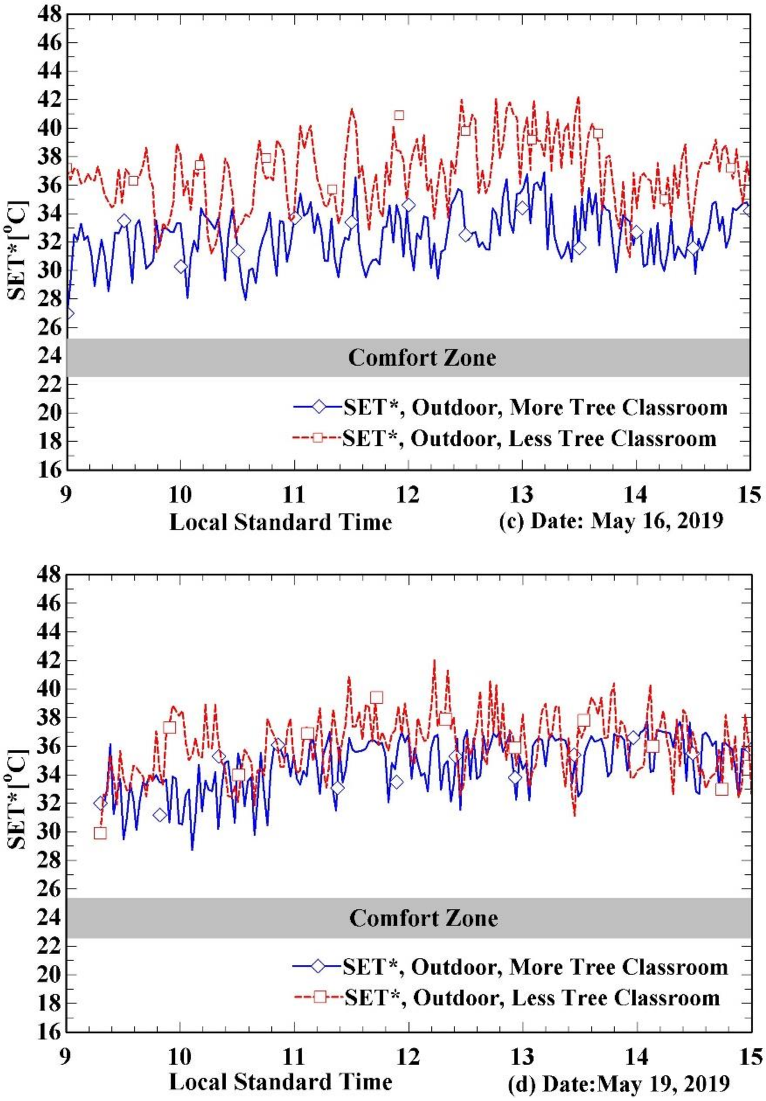


Figure 5.4 Outdoor SET* Trend of More Tree and Less Tree Classroom

Other than May 19, the SET* values outside of Classroom surrounded by More Tree were found slightly lower than its indoor counterpart. The lowest outdoor SET* values were evident as 25.5°C with 'Comfortable and Acceptable' sensation on May 14 and 27°C with 'Slightly Warm' sensation on May 16. Lower air temperature along with mentionable air velocity resulted lower outdoor SET* values during those periods. The outdoor air temperature and relative humidity were recorded higher on May 19, while the air velocity was lower compared to other measurement dates. The highest outdoor SET* values were found as 37.7°C with 'Very Hot' sensation on May 19. Apart from this, higher SET* value was determined as 36.2°C with 'Hot' sensation on May 16 resulted from higher air temperature and still air.

For Classroom surrounded by Less Tree, the outdoor SET* was lower up to 10:00 LST on May 13 resulted from lower air temperature. The lowest outdoor SET* was calculated as 30.6°C with a ‘Warm’ sensation during this period. On May 19, the outdoor SET* values were started to fall between 14:30 and 15:00 LST due to the presence of increased air velocity. During this period, the lowest outdoor SET* was calculated as 32.4°C with ‘Warm’ sensation when the air velocity was 1.75ms^{-1}. The outdoor SET* values were found higher than indoor SET* in rest of the measurement periods. The average outdoor SET* value (36.7°C) for Classroom surrounded by Less Tree was higher on May 16 due to higher average outdoor air temperature (38.6°C). The highest outdoor SET* values were calculated as 43.2°C on May 13 and 42°C with ‘Very Hot’ sensation on May 16 due to high air temperature and still air.

5.3 Case 3: Thermal Comfort Comparison between Lakeside Classroom and Non-lakeside Classroom

Calculated values of the indoor and outdoor SET* in different measurement dates are plotted in Figure 5.5. The SET* values inside classrooms were found more stable than its outdoor counterparts in response to the steady change of indoor weather parameters.

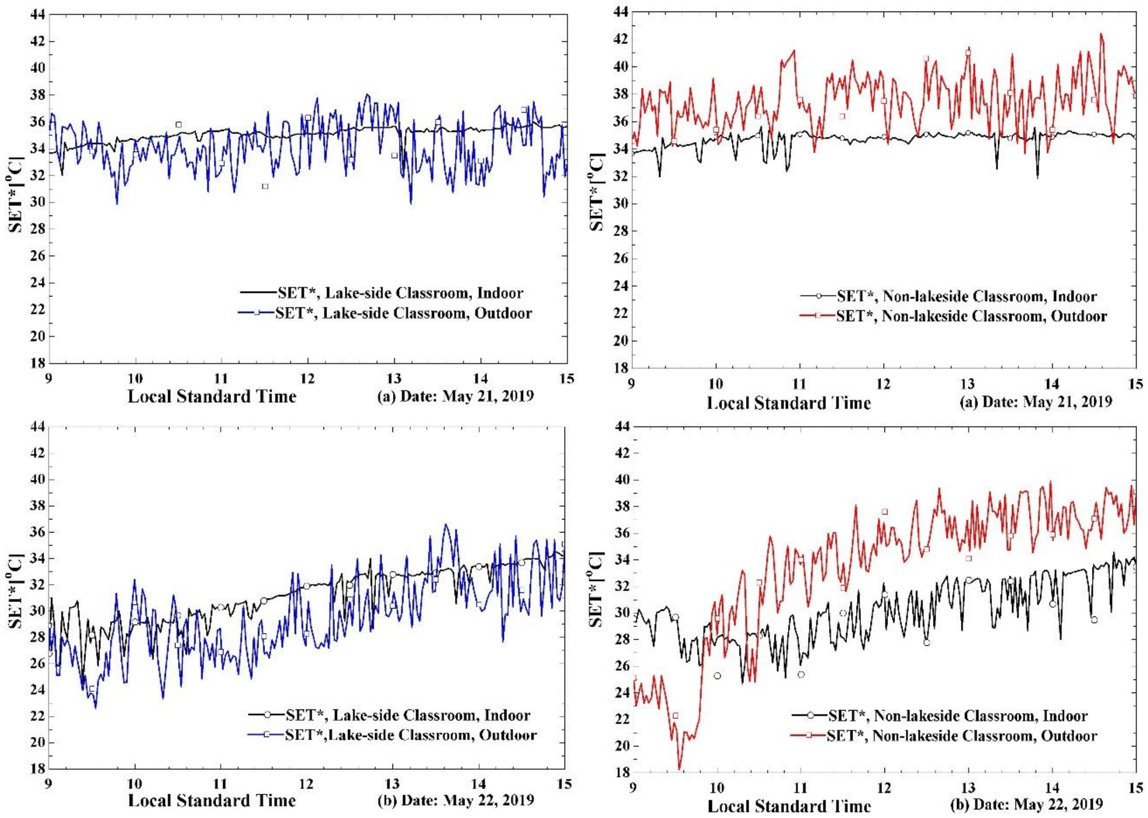


Figure 5.5 Indoor and Outdoor SET* in Lakeside and Non-lakeside Classroom [Continue in next page]

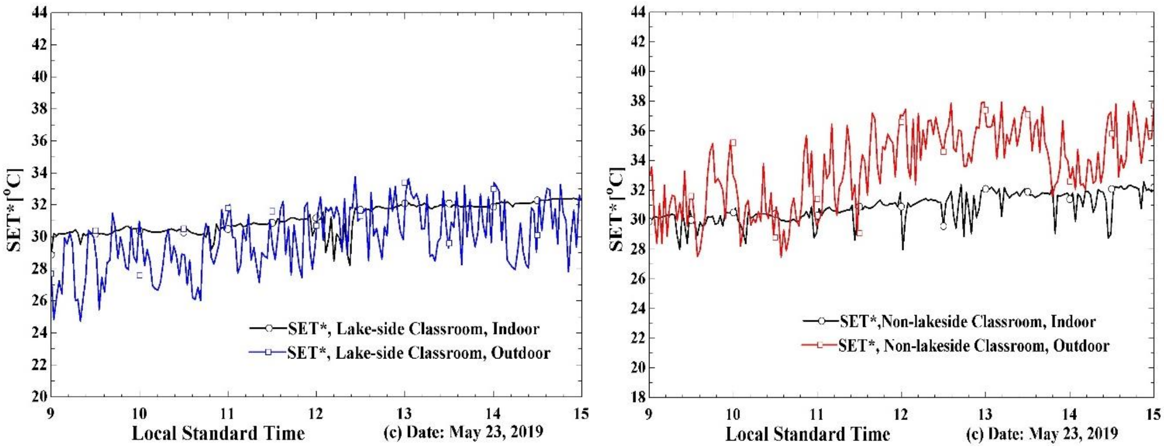


Figure 5.5 Indoor and Outdoor SET* in Lakeside and Non-Lakeside Classroom

The outdoor SET* values of the lakeside classroom were found lower than the indoor SET* values (Figure 5.5). The lakeside classroom was located on the top floor of a three storied building and exposed more to the direct solar radiation. Therefore, the indoor air temperature of lakeside classroom was higher. At the same time air inside the lakeside classroom was remain almost still which resulted higher indoor SET* values. On the other hand, the outdoor SET* values were higher than the indoor in non-lakeside classroom (Figure 5.5). The outdoor air temperature was higher than the indoor and thus resulted higher outdoor SET* values.

5.3.1 Indoor Thermal Comfort Analysis of Case 3

The calculated outdoor SET* values for Non-lakeside Classroom were much higher than that of indoor in most of the measurement periods. However, in the case of Lakeside Classroom, the scenario was a little different. The SET* values were low inside the classrooms (Figure 5.6) in the morning and then, in response to the increase in air temperature, started to increase steadily. Similar air temperature up to10:30 and 10:00 LST on May 21 and 23, respectively, resulted in an almost similar trend of SET* values. The SET* values were evident slightly higher in Lakeside Classroom than Non-lakeside Classroom, especially on May 22. The maximum average difference between the indoor SET* values of Lakeside and Non-lakeside Classroom was 0.6°C during that date. These differences were determined as 0.4°C and 0.3°C on May 21 and 23, respectively. The lakeside classroom was located on the top floor of a three-storied building. So, heat gain from the roof was higher. In addition, windows were on the east-facing exterior wall, which also causes additional heat gain. Therefore, the cooling effect of lake in this classroom was found negligible. However, the cooling effect of lake were clearly visible in the outdoor space near lake compared to the non-lake outdoor space. If the lakeside classroom was not located in the top floor, the colling effect of lake might be more visible. To examine the cooling effect of lake, simulation study will be conducted in Chapter 6 considering the outdoor air temperature of lakeside space. The indoor SET* values of Non-lakeside Classroom fluctuate more than Lakeside Classroom because of frequent air velocity.

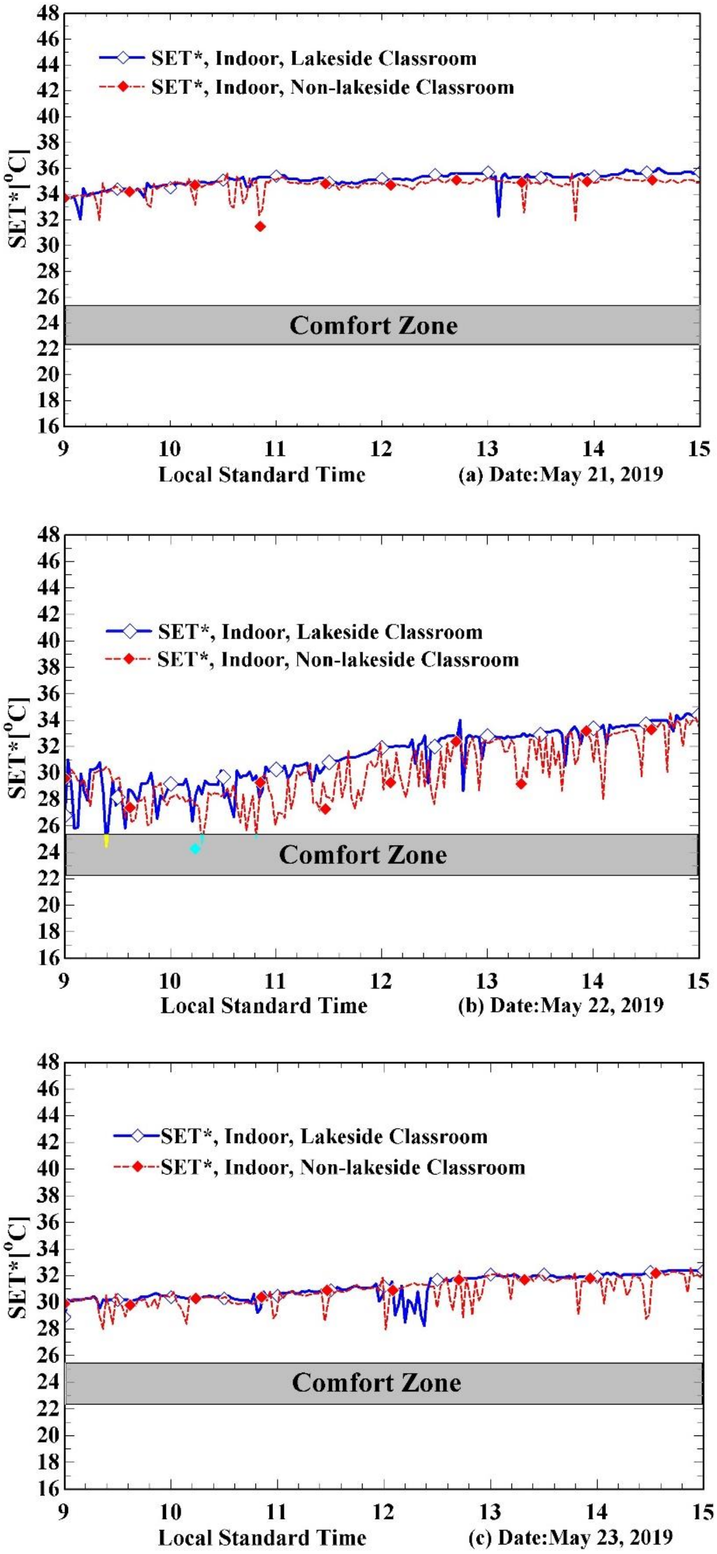


Figure 5.6 Indoor SET* Trend of Lakeside and Non-lakeside Classroom

On May 22, the indoor SET* values were closer to the ASHRAE-17 recommended comfort zone up to 10:30 LST During this period, the minimum SET* values were calculated as 23.3^oC in Lakeside Classroom and 24.3^oC in Non-lakeside Classroom with a sensation of 'Comfortable and Acceptable'. Lower air temperature coupled with notable air velocity yielded such comfort zone in SET* index. The SET* values were also found closer to the ASHRAE-17 recommended comfort zone on May 23 between 12:07 to 12:21 LST in Lakeside Classroom and 12:44 to 12:55 LST in Non-lakeside Classroom. During these periods, ceiling fans were in operation and the lowest SET* values were calculated as 27.3^oC in Lakeside Classroom and 28.8^oC in Non-lakeside Classroom with a 'Slightly Warm' sensation.

Higher indoor SET* values were found in both classrooms due to higher air temperature on May 21. The highest SET* value was estimated as 36^oC ('Hot' Sensation) with an average of 35.1^oC in Lakeside Classroom and 35.3^oC ('Hot' Sensation) with average of 34.7^oC in Non-lakeside Classroom on that date. The lower average air temperature dropped the average indoor SET* down on May 22 and 23. The average SET* values were 31.2^oC and 31.1^oC in Lakeside Classroom, while 30.1^oC and 30.8^oC in Non-lakeside Classroom on those dates, respectively. Apart from May 21, the highest SET* values were calculated as 34.7^oC in Lakeside Classroom and 34.3^oC in Non-lakeside Classroom on May 22.

5.3.2 Outdoor Thermal Comfort Analysis of Case 3

The SET* values outside of Lakeside Classroom were found lower than Non-lakeside Classroom (Figure 5.7) in most of time expect between 9:00 and 9:50 LST on May 22 (Figure 5.7 (b)). The outdoor weather was cloudy and the air temperature near non-lakeside was found lower than lakeside outdoor during that period. The outdoor average SET* values of Lakeside Classroom and Non-lakeside Classroom were 26^oC and 23.8^oC, respectively, up to 10:00 LST on that day. The lower air temperature (26.3^oC) and mentionable air velocity (0.9 ms^{-1}) outside of the Non-lakeside Classroom resulted such lower SET* during that time. The lowest SET* values were calculated as 18.7^oC and 22.2^oC with 'Slightly Cool' sensation outside of Lakeside Classroom and Non-lakeside Classroom respectively on that period. The maximum outdoor SET* of Non-lakeside Classroom was calculated as 42.7^oC with 'Very Hot' sensation on May 21 and 40.7^oC with 'Very Hot' sensation on May 22. In case of Lakeside Classroom, the maximum outdoor SET* were found as 38.1^oC with a 'Very Hot' sensation on May 21, followed by 36.9^oC with 'Hot' sensation on May 22.

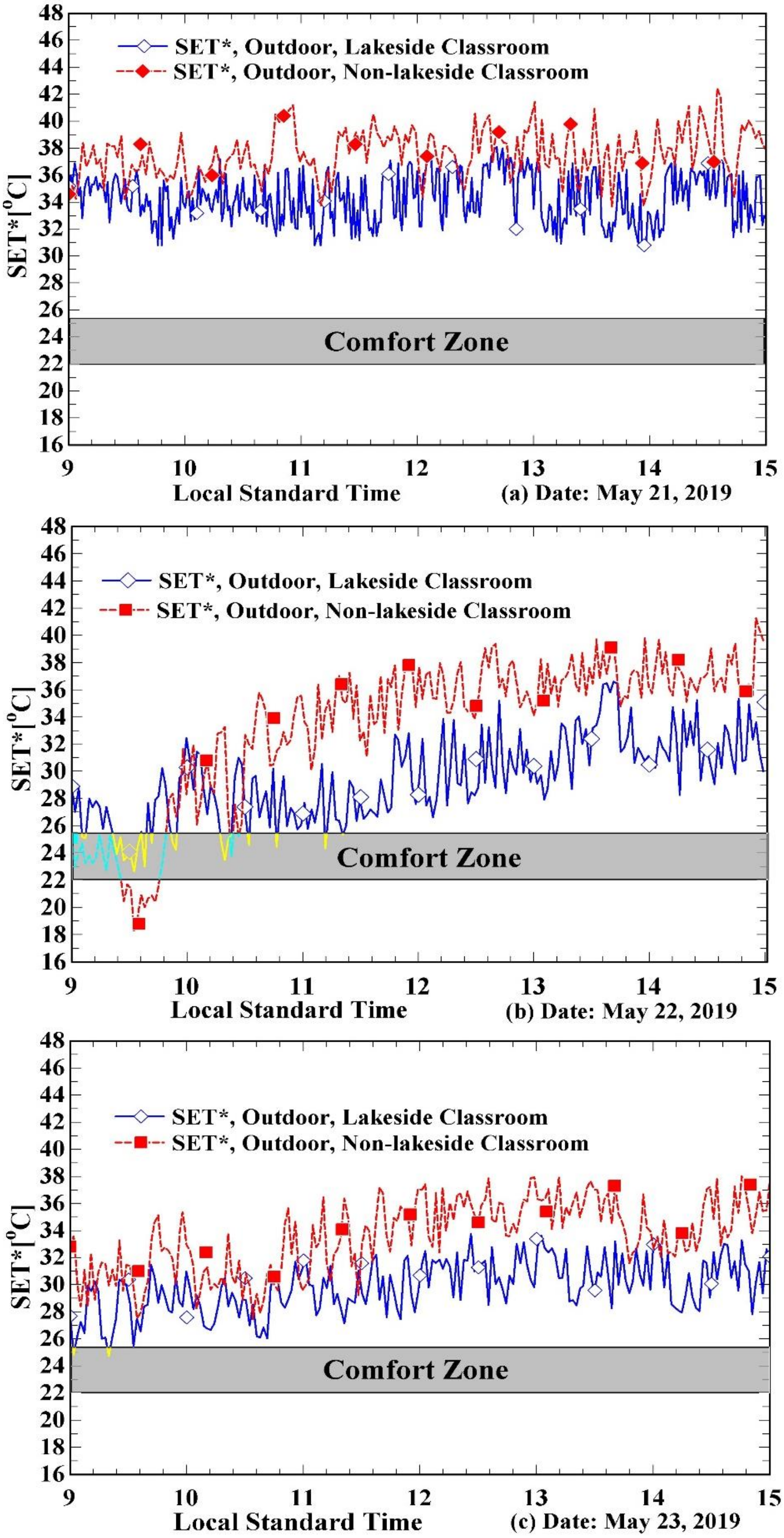


Figure 5.7 Outdoor SET* Trend of Lakeside and Non-lakeside Classroom

The average SET* values outside of Lakeside Classroom were calculated as 34.3^{o}C ('Warm' sensation), 29.4^{o}C ('Slightly Warm' sensation), and 29.9^{o}C ('Slightly Warm' sensation) on May 21, 22, and 23, respectively. While for Non-lakeside Classroom, the average outdoor SET* values were found as 37.6^{o}C ('Very Hot' sensation), 33.3^{o}C ('Warm' sensation), and 33.6^{o}C ('Warm' sensation) on the same dates. The 'Comfortable and Acceptable' SET* values were determined outside of Lakeside Classroom between 9:27 and 9:43 LST, 9:57 and 9:59 LST, and 10:23 and 10:26 LST on May 22. On the same date between 9:00 and 9:10 LST, and 9:16 and 9:26 LST, the SET* values were found 'Comfortable and Acceptable' outside of the Non-lakeside Classroom. The outdoor air temperature and air velocity were higher in non-lakeside space than lakeside space. Higher fluctuation in outdoor air velocity resulted sudden change in the outdoor SET* values in non-lakeside outdoor space. Though outdoor SET* values changed more frequently in response to weather parameters, the overall comfort index trend of Lakeside Classroom was found closer to the standard comfort zone. The high thermal capacity of the lake and evaporation process reduced the air temperature and thereby dropped the SET* values down at the surrounding space of Lakeside Classroom.

5.4 Case 4: Thermal Comfort Comparison between Classrooms with Large Window Area and Small Window Area

The indoor and outdoor SET* trends in different dates are presented in Figure 5. 8 and Figure 5.9, respectively. The indoor SET* values of small window classroom were relatively stable on May 29, and 30. Conversely, the indoor SET* values in the large window classroom change frequently on those dates. Larger windows allowed more air circulation inside the classroom and influenced the SET* values. On June 15, indoor SET* values of the classrooms were found relatively stable. On that day, the outdoor air velocity was comparatively lower and thus less influence was observed on the indoor SET* values of large window classroom.

5.4.1 Indoor Thermal Comfort Analysis of Case 4

The mean SET* values inside Small Window Classroom was 2.1^{o}C and 2.2^{o}C higher than Large Window Classroom on May 29 and 30, respectively. In Large Window Classroom, the minimum SET* values were determined as 28^{o}C and 28.7^{o}C with 'Slightly Warm' sensation on May 30 and 29 respectively. Conversely, inside Small Window Classroom, the minimum SET* values were calculated as 33.5^{o}C with 'Warm' sensation and 28.8^{o}C with 'Slightly Warm' on May 29 and 30 respectively. However, the maximum SET* values were calculated as 35.8^{o}C and 35.5^{o}C with 'Hot' sensation inside Large Window Classroom on May 29 and 30 respectively. On the same dates, the maximum SET* values were calculated as 35.7°C and 35°C with 'Hot' sensation respectively inside Small Window Classroom.

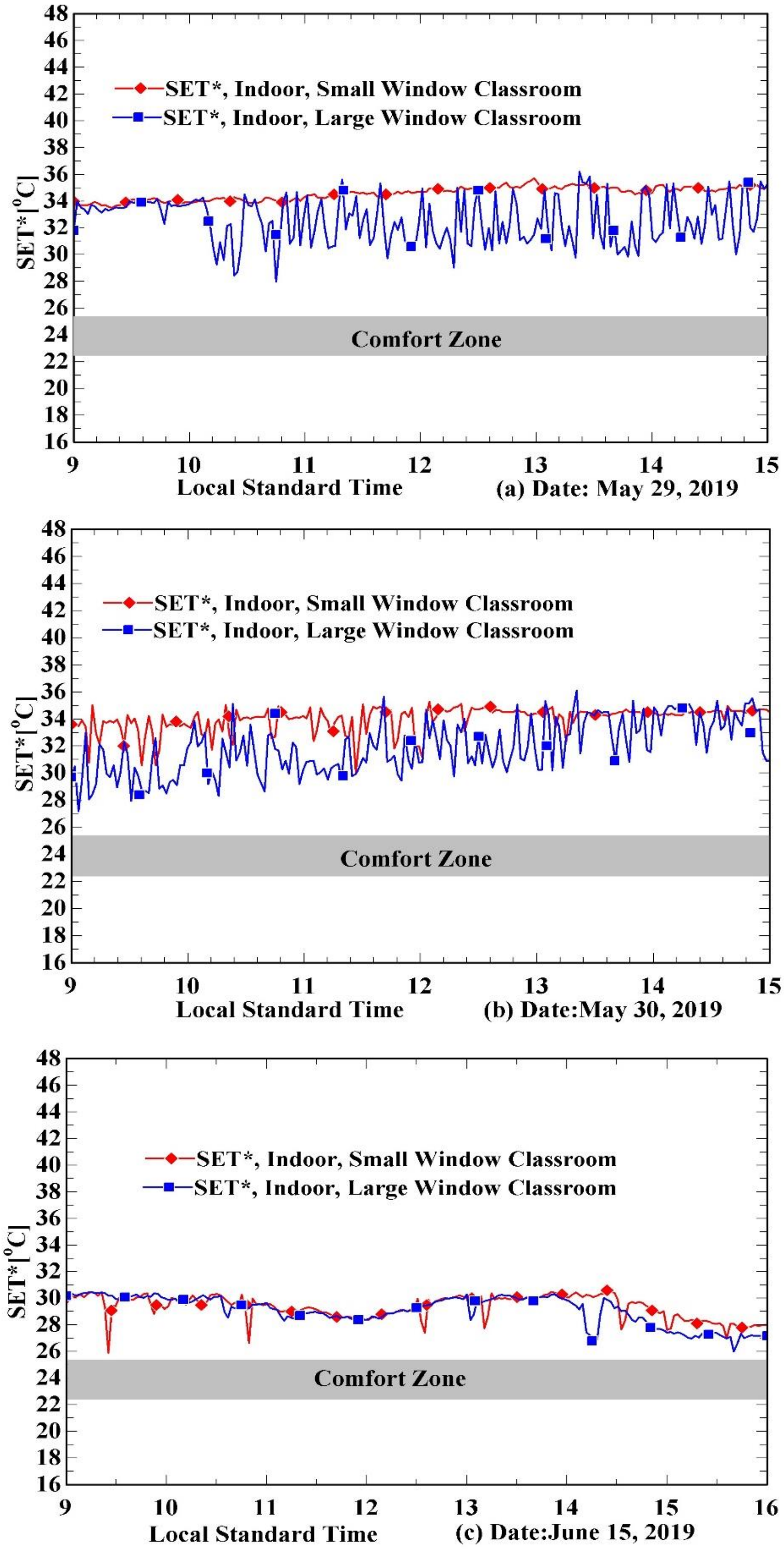


Figure 5.8 Indoor SET* Trend of Small and Large Window Classroom

The SET* values inside Large Window Classroom fluctuated more than Small Window Classroom on May 29 and 30. On those dates the measured air temperatures were quite similar in both classrooms. However, the provision of consistent air flow resulted frequent change in the comfort index values. On June 15, the SET* values in both classrooms were found stable because of lower air velocity.

On June 15, the indoor SET* values of the classrooms were found quite similar up to 13:50 LST and then the index values of Large Window Classroom started to decrease in greater extent than Small Window Classroom. During that period the minimum SET* value was calculated as 25.2^{o}C with 'Comfortable and Acceptable' sensation in Large Window Classroom and 25.8^{o}C with 'Slightly Warm' sensation in Small Window Classroom. The mean SET* values were determined as 29.3^{o}C in Small Window Classroom and 29.1^{o}C in Large Window Classroom on June 15 when the maximum SET* value was found as 30.6^{o}C with 'Warm' sensation. The ceiling fans were in operation in Small Window Classroom between 14:29 and 14:40 LST and in Large Window Classroom from 14:10 to 14:21 LST on May 15. The minimum SET* value was calculated as 27.2^{o}C in Small Window Classroom and 26.6^{o}C in Large Window Classroom with 'Slightly Warm' sensation during those periods. On June 15, the indoor air temperature of both the classrooms were found very closer. Moreover, outdoor air velocities of the classrooms were measured lower compared to other dates. The large window classroom could not receive much air from the outside compared to other dates. Similar air temperature and air velocity of the classrooms resulted a closer indoor SET* trends on June 15.

5.4.2 Outdoor Thermal Comfort Analysis of Case 4

The mean SET* values outside of Small Window Classroom was 37.7^{o}C on May 29 and 37.3^{o}C on May 30. For this classroom, the highest SET* values were calculated as 43.9^{o}C on May 20 and 43.6^{o}C on May 30 with 'Hot' sensation. On the same date the lowest SET* values were calculated as 31.3^{o}C and 30.6^{o}C respectively with 'Warm' sensation.

The mean outdoor SET* values of Large Window Classroom were 37.6^{o}C on May 29 and 36.8^{o}C on May 30. Outside of this classroom, the highest SET* values were calculated as 43.9^{o}C on May 29 and 43.6^{o}C on May 30 with 'Very Hot' sensation. Conversely, the minimum outdoor SET* values were calculated as 29.4^{o}C on May 30 and 30^{o}C on May 29 with 'Slightly Warm' sensation.

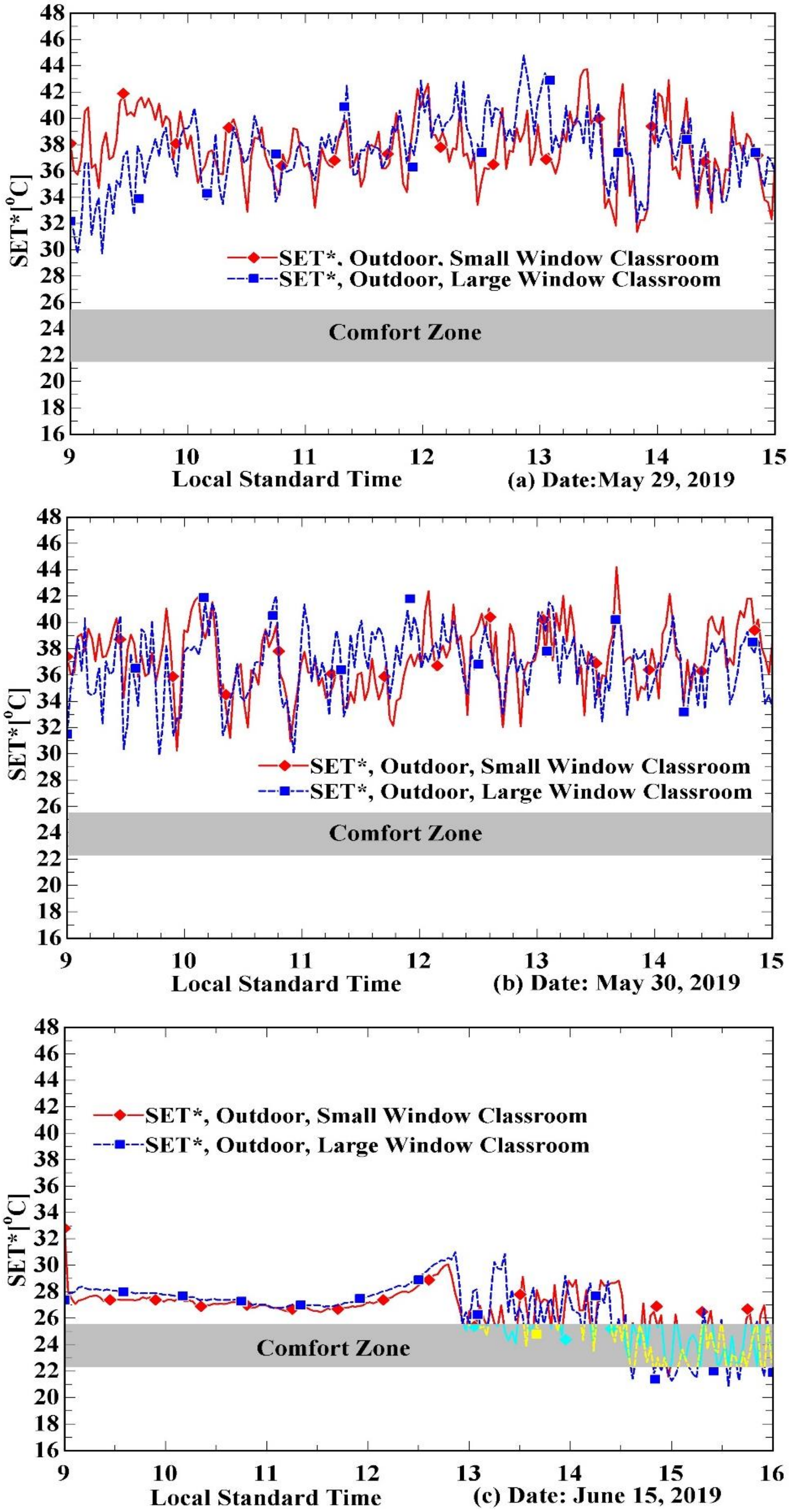


Figure 5.9 Outdoor SET* Trend of Small and Large Window Classroom

On June 15, the outdoor weather was overcast, and the outdoor air temperatures were also lower compared to other measurement dates. As a result, the outdoor SET* values were lower on June 15 for both the classrooms. The mean outdoor SET* value was 26.7ºC for Small Window Classroom and 26.6ºC for Large Window Classroom. Furthermore, the outdoor SET* values were relatively higher and steady around 13:00 LST because of almost still air. After that period, a decreasing trend in air temperature along with increased air velocity dropped the outdoor SET* values. On that date the outdoor SET* values of Small Window Classroom were slightly lower than Large Window Classroom up to 13:00 LST and after that a reversed situation was observed (Figure 5.9(c)). The minimum outdoor SET* value was calculated as 21.2ºC for Small Window Classroom and 21ºC for Large Window Classroom with 'Slightly Cool' sensation.

5.5 Case 5: Thermal Comfort Evaluation of Studio Type Classroom

Apart from June 13, outdoor SET* values were found higher than that in indoor. Outdoor SET* values also fluctuate more as outdoor environmental parameters changed more frequently. As the time progresses, the SET* values inside the classroom approach in a comparatively steady manner (Figure 5.10) during all the measurement dates.

5.5.1 Indoor Thermal Comfort Analysis of Case 5

The mean SET* values inside the Studio type Classroom was determined as 36.1℃ on June 11, 37.1℃ on June 12, and 36.4℃ on June 13. The indoor air temperatures and relative humidity were higher on June 12, and the highest SET* value was estimated at 37.7℃. This SET* value indicates "Very Hot" sensation which is very uncomfortable for the occupants. The maximum SET* value was calculated as 36.6℃ with 'Hot' sensation on June 11. Besides, the minimum calculated SET* values were 35.4℃ on June 11, and 36.4℃ on June 12 with 'Hot' sensation. On June 13, SET* values inside classroom were found comparatively lower up to 11:50 LST than those of June 11 and 12. Ceiling fans were in operation between 11:38 and 11:51 LST on June 13 when the maximum air velocity was recorded as 1.11 ms^{-1}. Consequently, the lowest SET* value was found as 32.4℃ ('warm' sensation) inside classroom in that period. However, absence of air velocity and higher air temperature resulted the maximum SET* value of 37.4℃ with 'Hot' sensation on the same date.

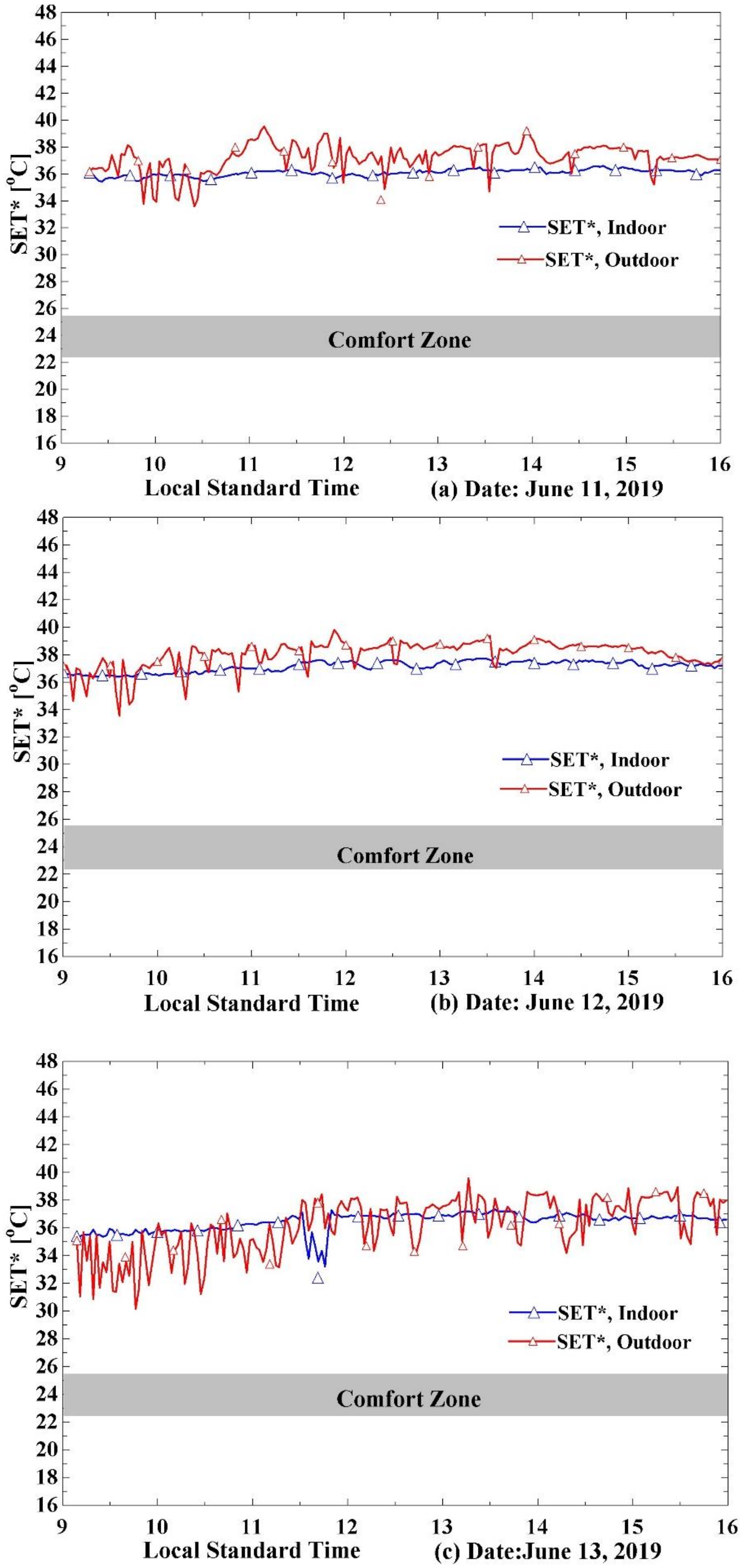


Figure 5.10 Indoor and Outdoor SET* Trend of Studio Type Classroom

5.5.2 Outdoor Thermal Comfort Analysis of Case 5

The mean outdoor SET* was calculated as 37.2℃ on June 11, 38.0℃ on June 12, and 36.2℃ on June 13. Figure 5.10(c) indicates that outdoor SET* fluctuates wildly on June 13. Though the outside temperature trend remained comparatively stable, the air velocity frequently fluctuates to a greater extent during that date. For example, between 10:27 and 10:31 LST on June 13, air velocity was measured as 0.0, 0.9, 0.2, 0.0, and 0.5 ms^{-1} respectively along with 30.8℃, 30.7℃, 30.7℃, 30.7℃, and 30.7℃ air temperature. The calculated SET* values during this period also varied largely in response to change in air velocity. Similar fluctuations in outdoor SET* values were also observed on other measurement dates in response to the change in air velocity. Because of higher air temperature and very low air velocity, the maximum outdoor SET* value was determined as 40^{o}C ('Very Hot' sensation) on June 12 followed by 39.7℃ ('Very Hot' sensation) on June 11. Outdoor SET* values were lower up to 11:30 LST, June 13 with a minimum SET* value of 30.3℃ and 'Warm' in sensation scale. An outside condition during this period was cloudy, and air temperature; globe temperature found comparatively lower with notable air velocity (1.2 ms^{-1}). Besides, minimum outdoor SET* was 32℃ on June 11, and 32.5℃ on June 12 with 'Warm' sensation.

5.6 Case 6: Thermal Comfort Evaluation of Seminar Library

The indoor and outdoor SET* trend of the Seminar Library is plotted in Figure 5.11. Apart from the morning period on June 13, the outdoor SET* values were found higher than its indoor counterpart.

5.6.1 Indoor Thermal Comfort Analysis of Case 6

The mean indoor SET* values were found lower (32.5^{o}C) on June 11 and higher (34.4^{o}C) on June 12. Provision of consistent air flow by operating ceiling fans kept the indoor SET* values lower during the entire measurement period on June 11. The minimum indoor SET* value was calculated as 28.6^{o}C with 'Slightly Warm' sensation in that date. On June 12, the indoor SET* values were remained lower between 9:29 and 13:01 LST when ceiling fans were also remained switched on. During this period the minimum indoor SET* value was calculated as 29.5^{o}C with 'Slightly Warm' sensation. The ceiling fans were also in operation between 12:21 and12:39 LST on June 13. Consequently, the SET* values dropped during that period when the minimum SET* value was calculated as 31.9^{o}C with 'Warm' sensation. The highest indoor SET* value was calculated as 36.6^{o}C and 36.1^{o}C on June 12 and 13 respectively with 'Hot' sensation resulted from higher air temperature and still air.

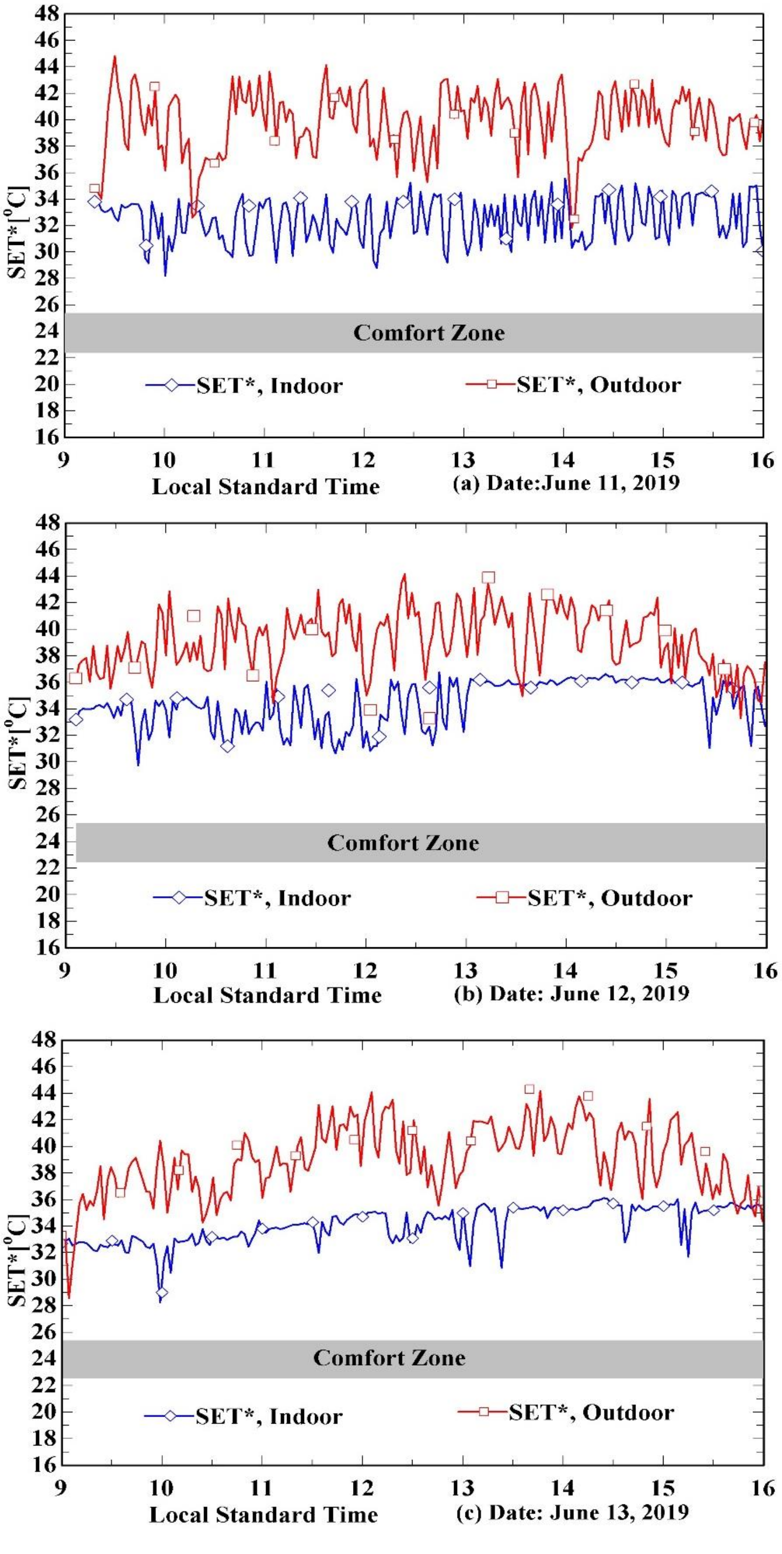


Figure 5.11 Indoor and Outdoor SET* Trend of Seminar Library

5.6.2 Outdoor Thermal Comfort Analysis of Case 6

The mean outdoor SET* values were calculated as 39.8°C on June 11, 39.1°C on June 12, and 38.9°C on June 13. The highest outdoor SET* value was calculated as 45°C on June 11, followed by 44.7°C on June 13 and 43.9°C on June 12 with 'Very Hot' sensation because of high air temperature and lowest air velocity. The minimum outdoor SET* value was calculated as 28.7°C with 'Slightly Warm' sensation on June 13. The lower air temperature (30.9°C) coupled with mentionable air velocity (1.1 ms^{-1}) made the SET* value closer the standard comfort zone. On June 11, the outdoor SET* values dropped sharply around 14:08 LST because of sharp increase in air velocity along with a decrease in air temperature. During this period, the outdoor SET* value was determined as 32.2°C with 'Warm' sensation. On June 12, the outdoor SET* values started to tumble down between 15:27 and 15:57 LST because of notable air velocity and decrease in air temperature. The minimum SET* value was determined as 32.4°C with 'Warm' sensation during that period.

5.7 Conclusion

This is observed that, the weather parameters especially air temperature and air velocity have a notable effect on the comfort index. Consequently, the outdoor SET* values fluctuate more than the indoor SET*. The outdoor SET* trend was found higher than the indoor SET* trend in response to the higher outdoor air temperature. Likewise weather parameters, the indoor SET* trend showed the correspondence with the outdoor SET* trend. The outdoor and indoor SET* values of Classroom surrounded by more trees were lower than Classroom surrounded by less tree. Providing solar protection through shading, absorbing solar radiation, affecting air movement, and evapotranspiration processes trees are capable to lower down the air temperature considerably. In addition, lake can contribute to the reduction of outdoor air temperature compared to the non-lakeside space. Concurrently, the mean SET* values near the lake was lower than the non-lakeside space. The high thermal capacity of the lake and evaporation process reduced the air temperature and thereby dropped the SET* values down at the surrounding space of lakeside classroom. In field measurement the lakeside classroom was located on the top floor of a three storied building, which was exposed more to solar radiation. The non-lakeside classroom was not located on the top floor and thereby air temperature was found slightly lower than in lakeside classroom. Thus, in comparing with non-lakeside indoor air temperature and comfort index value slightly different scenario was observed. In all cases the increased air velocity reduced both the outdoor and indoor SET* values. The overall SET* values indicate the comfort condition in indoor and outdoor are away from the standard comfort zone. Therefore, this is necessary to focus on air temperature reduction and air velocity augmentation to achieve desirable thermal environment.

Chapter 6

Effect of Outdoor Environmental Settings on Indoor Thermal Environment

First, the calibration procedure of the simulation program along with the preliminary model for calibration are described in this chapter. Second, after comparing the matching trend between measurement results and simulation results, the preliminary model will be fixed. Finally, a parametric study with different environmental settings' weather data will be carried out.

6.1 Calibration Procedure for Weather Data Validation

Calibration has been considered as an important factor to substantiate the simulation program with the field measurement data. The simulated indoor air temperature (hourly) during the baseline period of May was compared with the measured air temperature. The calibrated model will be used to evaluate the indoor thermal environment in different outdoor environmental settings. The calibration procedure of this study is illustrated in Figure 6.1.

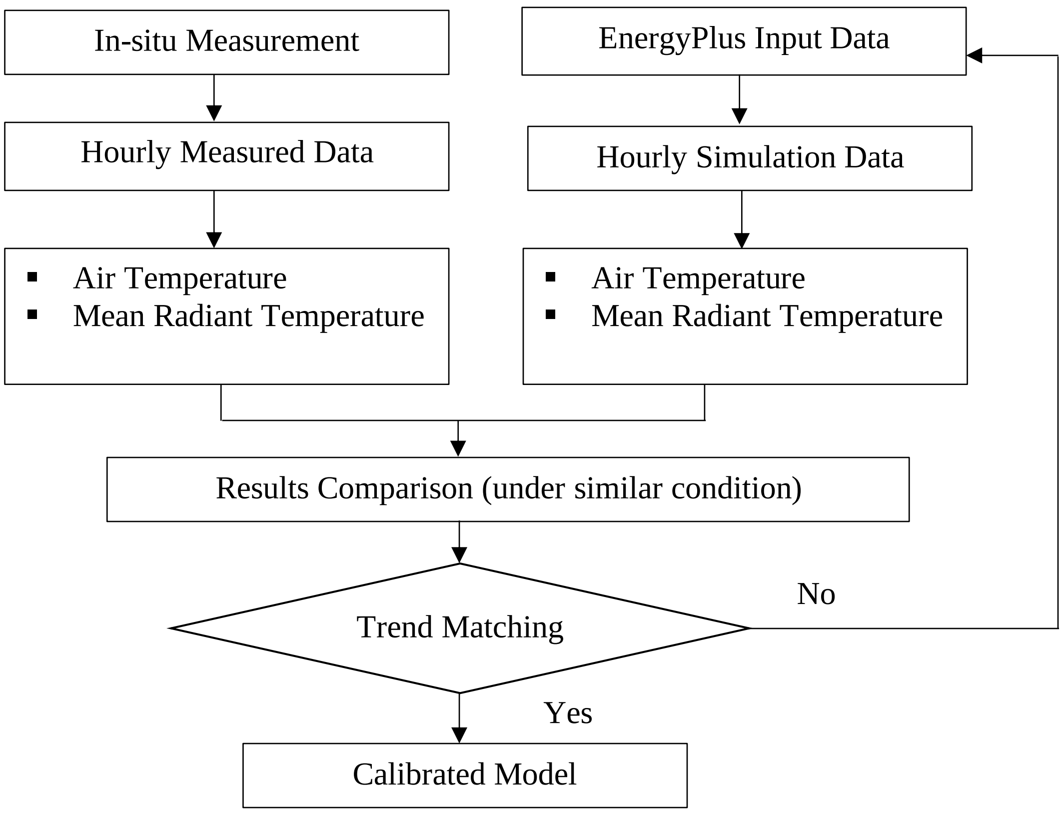


Figure 6.1 Calibration Process

The calibration process is composed of two parts. First, the EnergyPlus model based on information obtained from building specifications is inputted. Dhaka.419230_SWERA.epw was used as weather data. The Solar and Wind Energy Resource Assessment (SWERA) project, funded by the United Nations Environment Program provides high quality weather data. Second, the hourly results extracted from the simulation are compared with measurement results.

Weather parameters related to thermal comfort were recorded in the one-minute intervals during field measurement. For results comparison, one-minute time interval data have been converted to hourly data. To find out the matching trend, indoor air temperature and mean radiant temperature of the simulation results and the measurement results have been compared. Finding the matching trend, the calibrated model has been used as an initial model for further evaluation.

The purpose of calibration is to ensure that the model can generate the results close to the measured results. Thus, the actual input especially site-specific measured weather data should be concerned. In this study, only some weather parameters i.e., air temperature, relative humidity, wind velocity, solar radiation were measured. The data sources from field measurement are insufficient to customize the accurate weather data for simulation. Field measurement was carried out during the vacation period of the university. During vacation the number of people was minimum and electrical equipment were switched off in most of the time. The internal gains from people's influence, lighting, and electrical equipment are neglected in this study. The classroom with long façade facing on west direction was selected for calibration.

6.2 Preliminary Model for Calibration Procedure

The preliminary model is configured according to the construction drawing and an outline specification of the building before running the simulation. The general data input can be categorized mainly as location (Table 6.1), surface construction element, and thermal zones.

Table 6.1 Location of Study Site

Input Parameter	Input Data
Site Name	Dhaka, Bangladesh (BGD)
Latitude, and Longitude	23.77 N, and 90.38 E
Time Zone	6:00+ GMT
Elevation [m]	9.00

Construction materials are defined for walls, floor, ceiling, doors, and windows. The construction materials and the number of material layers present in that construction are presented in Table 6.2.

Table 6.2 Input Data of the Construction Elements

Construction Element	Construction Layer	Construction Material
Exterior wall	Outside layer	Plastering
	Layer 2	Brick
	Layer 3	Plastering
Interior wall	Outside layer	Plastering
	Layer 2	Brick
	Layer 3	Plastering
Floor	Outside layer	Tile
	Layer 2	Concrete
Ceiling	Outside layer	Concrete
	Layer 2	Plastering
Door	Outside layer	Wood
Window	Outside layer	Clear Glass 6 mm

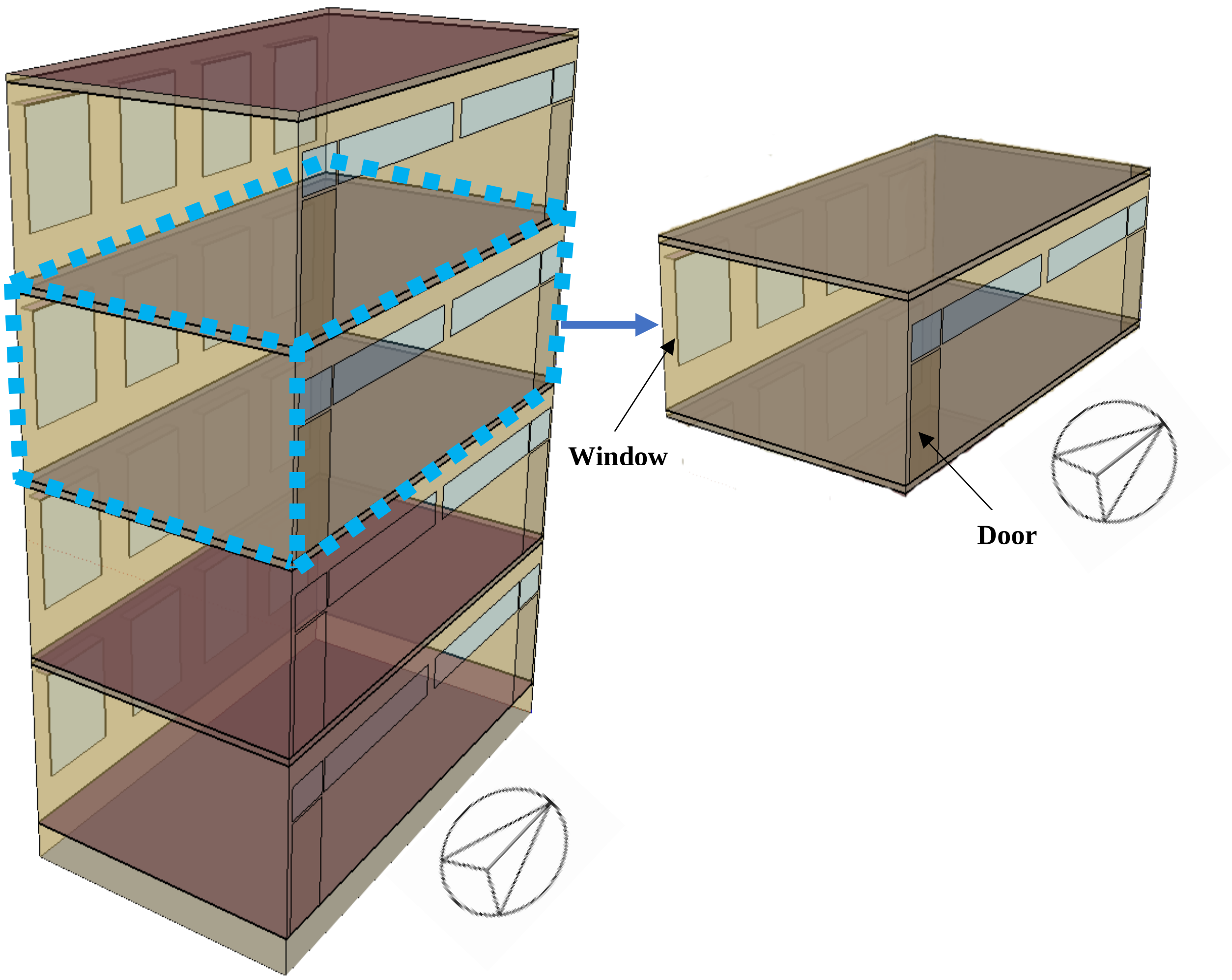


Figure 6.2 Preliminary Model for Calibration

The preliminary model for calibration is presented in Figure 6.2. The simulation model consists of three thermal zones e.g., floor, room, and ceiling. The model classroom is located on the 3rd floor of a four-storied building. The windows are on the west façade, and the doors are on the east-facing wall.

Table 6.3 Outline Specification and Thermal Properties of Construction Materials

Materials	Roughness	Thickness [mm]	Thermal properties		
			Density, ρ, [kg/m^3]	Conductivity, k, [W/(m·K)]	Specific Heat, Cp, [J/(kg·K)]
Plaster	Medium rough	10	2375	0.43	753
Brick	Smooth	107	1790	0.55	1172
Concrete	Medium rough	150	2487	1.34	670
Tile	Smooth	6.3	1764	1.12	1213
Wood	Medium smooth	25	608	0.15	1630

Table 6.4 Thermal Properties of Window Material (Clear 6 mm): Glazing

Thermal properties parameters	Value	Thermal properties parameters	Value
Solar Transmittance at Normal Incidence	0.837	Back Side Visible Reflectance at Normal Incidence	0.081
Front Side Solar Reflectance at Normal Incidence	0.075	Infrared Transmittance at Normal Incidence	0.00
Back Side Solar Reflectance at Normal Incidence	0.075	Front Side Infrared Hemispherical Emissivity	0.84
Visible Transmittance at Normal Incidence	0.898	Back Side Infrared Hemispherical Emissivity	0.84
Front Side Visible Reflectance at Normal Incidence	0.081	Conductivity [W/m·K]	0.90

Brick and plaster are the main construction materials of the wall. Concrete is used in floor and ceiling construction. The thermal properties of the construction materials are presented in Table 6.3. While Table 6.4 states the thermal properties of window material.

6.3 Comparison of Measurement and Simulation Results for Model Calibration

For calibration, indoor air temperature (T_a) and mean radiant temperature (MRT) were examined as comparison parameters. Figure 6.3 presents the comparison between measurement results and simulation results.

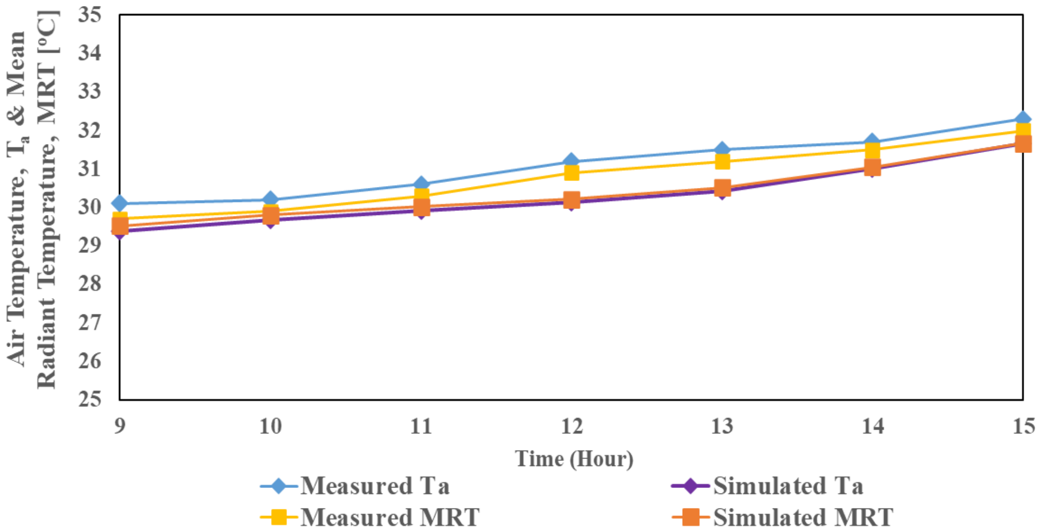


Figure 6.3 Comparison Between Measured and Simulated Results

Simulated results show the correspondence with measured results. Like measurement results, the indoor air temperature and mean radiant temperature form a similar trend in simulation results. The difference between the simulation results of mean radiant temperature and air temperature was slightly lower (0.4°C, and 0.7°C respectively) than the measured results.

The measured indoor air temperature and mean radiant temperature are found slightly higher than in simulation because of insufficient ventilation during field measurement. In the simulation, a constant air flow rate can be maintained. On the contrary, the air flow rate driven by natural ventilation does not constantly occur in real situations. Thereby, ventilation in simulation indicates slightly better performance than in the real situation. This model will be used as the base model for further investigation, as described in the following sections.

6.4 Effects of Outdoor Environmental Settings on Indoor Thermal Environment

One objective of this study is to examine the effects of outdoor environmental settings on the indoor thermal environment and comfort. Two different types of outdoor environmental settings e.g., tree area and lake have been considered in this study.

6.4.1 Procedure of New Weather Data Formation for EnergyPlus Simulation

EnergyPlus provides weather data of Dhaka for running simulation. However, weather data that incorporate the effect of trees and lakes on the indoor environment is rational in running simulation. Therefore, two new weather files have been created incorporating configured air temperature and relative humidity from 'Classroom surrounded by Tree', and 'Lakeside Classroom' cases. Figure 6.4 illustrates the process of new weather file formation for 'Tree' and 'Lake' cases.

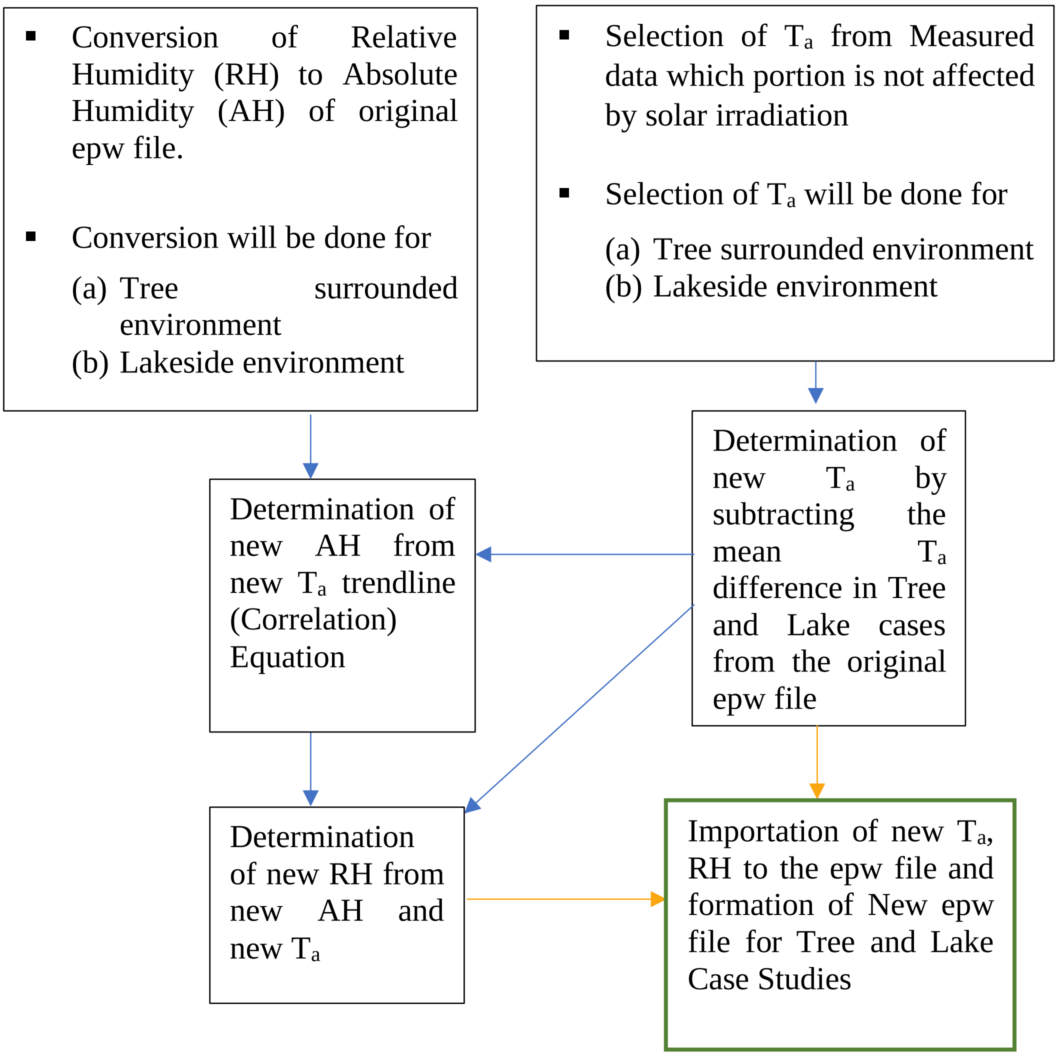


Figure 6.4 New Weather File Formation Process

Table 6.5 states the cooling effects of trees and lakes in different circumstances. The mean T_a difference between 'More Tree' and 'Less Tree' area has been determined from the measured weather data. The measured data were sometimes affected by the solar irradiation. Consequently, the T_a differences between 'More Tree' and 'Less Tree' area were found higher (Table 6.5) in some periods. To get more accurate results from simulation study, the T_a affected by the solar irradiation have been avoided. The mean difference of T_a between 'More Tree' and 'Less Tree' area was used to determine the new T_a for the modified weather file when the T_a was not affected by the solar irradiation.

Table 6.5 Cooling Effects of Trees and Lakes in Different Situations

Outdoor Weather Settings	Cooling Effects: Measured Data Affected by Solar Irradiation	Cooling Effects: Measured Data Not Affected by Solar Irradiation	Cooling Effects: Previous Studies
Cooling Effect of Tree	More than 1.5^{o}C	1.5^{o}C	1.5^{o}C
Cooling Effect of Lake	More than 1^{o}C	1^{o}C	1^{o}C

In case of tree, the mean T_a difference was determined as 1.5^{o}C and used to determine the new T_a in the tree's effects modified epw file. Such mean difference of T_a is well consistent with the previous studies, e.g., Aram, García, Solgi, Mansournia, 2019, Anjos and Lopes, 2017. The measured weather data around Lakeside and Non-lakeside area were also sometimes affected by the solar irradiation. Therefore, in the same way as the 'Tree' case, the mean T_a difference between 'Lakeside' and 'Non-lakeside' areas has been determined to prepare the new epw modified by the lake's influence. In the 'Lake' case, the mean T_a difference was determined as 1^{o}C, which is well supported by the previous studies, e.g., Guo-yu et al., 2013, Hathway and Sharples 2012. Finally, considering 1.5^{o}C and 1.0^{o}C cooling effect of the tree, and lake, respectively, new epw files were created incorporating new air temperature influenced by trees and lakes. The new T_a has been determined by deducting 1.5^{o}C from the 'Original' epw file's T_a to incorporate trees' cooling effect. Similarly, to include the lake's cooling effect, the new T_a has been determined by subtracting 1 ^{o}C from the T_a of the 'Original' epw file. In new weather files, new air temperature and new relative humidity have been incorporated. Other weather parameters of the EnergyPlus original epw file are kept the same.

6.4.2 Converted Outdoor Environmental Settings

Two new weather files have been developed incorporating the outdoor effects of trees and lakes. The new weather files are named 'Tree epw' and 'Lake epw' in this dissertation. In the 'Tree epw' file, converted air temperature derived from the mean outdoor air temperature difference of more tree and less tree classrooms' subtracting from the air temperature of the 'Original epw' file has been incorporated. Similarly, the converted air temperature derived from the mean outdoor air temperature difference of lakeside and non-lakeside classrooms deducting from the air temperature of the 'Original epw' file has been included in the 'Lake epw' file. Figure 6.5 presents the comparison of an outdoor air temperature of the 'Original epw', 'Tree epw', and 'Lake epw' files considering similar weather conditions.

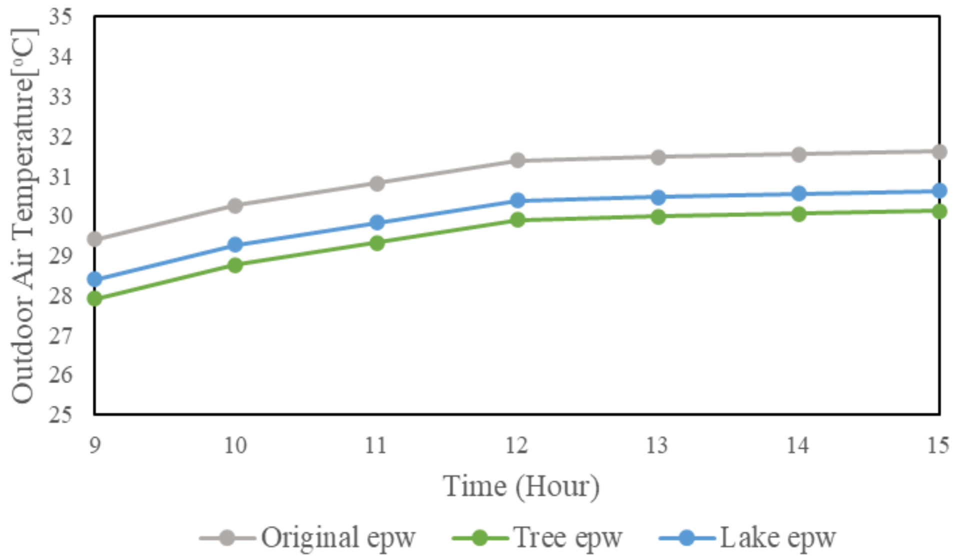


Figure 6.5 Outdoor Air Temperature Comparison of Different Weather File

This is observed that the outdoor air temperature derived from the 'Tree epw' and 'Lake epw' are lower than that of the 'Original epw.' This figure indicates that by introducing trees and lakes, outdoor air temperature could be reduced. In the following section, an attempt will be made to examine the effects of trees and lakes on the indoor thermal environment condition.

6.4.3 Parametric Study Conditions

The simulation study was carried out by considering construction material, ventilation schedule, ventilation rate, and outdoor weather conditions. Table 6.6 presents the overall conditions of the parametric study.

Table 6.6 Conditions for Parametric Study

Conditions	Condition Details
Material types	Material 1, Material 2, Material 3, Material 4, Material 5, Material 6, Material 7
Ventilation Schedule	Daytime schedule (8:00-17:00), Nighttime schedule (20:00-7:00)
Ventilation rate (air change/hour)	V_0=0/hr, V_{10}=10/hr, and V_{20}=20/hr
Outdoor weather conditions	Existing weather (Original epw), Modified weather by Tree (Tree epw), Modified weather by Lake (Lake epw)

Exterior wall influences the indoor thermal environment. Seven different types of material and construction patterns were used in the simulation study. Brick, concrete of different thicknesses, local tile, and plaster were considered in the construction of the exterior wall.

The exterior walls have an influence on the indoor thermal environment. To identify the best composition of materials and construction pattern of the exterior walls, a parametric study has been conducted. Table 6.7 presents the materials and construction pattern of the exterior wall for parametric study. The thermal properties of the construction materials are stated in Table 6.8.

Table 6.7 List of Construction Materials

Material option	Exterior wall construction pattern	Total Thickness [mm]
Material 1 (Base Case)	Plastering (outside layer, 10 mm) + Brick (107 mm) + Plastering (10 mm)	127
Material 2	Plastering (outside layer, 10 mm) + 150 mm Concrete + Plastering (10 mm)	170
Material 3	Tile (outside layer, 6.4 mm) + Brick (107 mm) + Plastering (10 mm)	123.4
Material 4	Brick (outside layer, 107 mm) + Plastering (10 mm) + Brick (107 mm) + Plastering (10 mm)	274
Material 5	Plastering (outside layer, 10 mm) + 200 mm Concrete + Plastering (10 mm)	220
Material 6	Tile (outside layer, 6.4 mm) + 150 mm Concrete + Plastering (10 mm)	166.4
Material 7	Tile (outside layer, 6.4 mm) + 200 mm Concrete + Plastering (10 mm)	216.4

Table 6.8 Thermal Properties of Construction Materials

Materials	Roughness	Thickness [mm]	Thermal properties Density, ρ, [kg/m^3]	Conductivity, k, [W/(m·K)]	Specific Heat, Cp, [J/(kg·K)]
Plaster	Medium rough	10	2375	0.43	753
Brick	Smooth	107	1790	0.55	1172
Concrete	Medium rough	150	2487	1.34	670
Tile	Smooth	6.3	1764	1.12	1213

In Bangladesh, plaster and brick are the most commonly used materials for the construction of exterior walls as well as interior walls. Thus, Material 1 in Table 6.6 is considered as the base case of the parametric study.

To examine the effects of the ventilation schedules, day and nighttime ventilation schedules were considered in simulation study. Daytime ventilation was fixed between 8:00-17:00, and nighttime ventilation ranged between 20:00-7:00 local standard time. At the same time, different ventilation rates (air change/hour) were also examined. The Simulation was run considering the above-mentioned conditions were in different outdoor weather conditions especially condition modified by trees and lakes, along with existing weather conditions.

6.4.4 Room Air Temperature Results of Parametric Study

The parametric study was conducted according to the conditions mentioned in Table 6.6 for one year period. In this section, the results of the parametric study have been summarized for a typical summer season week in the month of May. Firstly, daytime ventilation schedule results have been presented considering different construction materials, ventilation rates, in different weather conditions incorporating the effects of trees and lakes along with existing weather conditions. Table 6.9-6.11 present the indoor mean air temperature (8:00-17:00 LST) results when the daytime ventilation schedule was considered in operation along with different construction materials and different outdoor weather conditions including the effects of trees and lakes.

Table 6.9 Indoor Mean Air Temperature [^{o}C] in Daytime Ventilation Schedule, Original epw

Material Types	Ventilation Rates		
	V_0	V_{10}	V_{20}
Material-1	30.4	30.3	30.3
Material-2	30.4	30.3	30.3
Material-3	30.3	30.1	30.1
Material-4	30.4	30.1	30.1
Material-5	30.1	30.0	29.9
Material-6	30.2	30.0	30.0
Material-7	30.0	29.8	29.8

Table 6.10 Indoor Mean Air Temperature [^{o}C] in Daytime Ventilation Schedule, Lake epw

Material Types	Ventilation Rates		
	V_0	V_{10}	V_{20}
Material-1	29.8	29.6	29.6
Material-2	29.7	29.6	29.6
Material-3	29.7	29.5	29.4
Material-4	29.8	29.5	29.4
Material-5	29.4	29.3	29.3
Material-6	29.6	29.4	29.4
Material-7	29.3	29.2	29.2

Table 6.11 Indoor Mean Air Temperature [^oC] in Daytime Ventilation Schedule, Tree epw

Material Types	Ventilation Rates		
	V_0	V_{10}	V_{20}
Material-1	29.4	29.2	29.2
Material-2	29.4	29.2	29.2
Material-3	29.3	29.1	29.1
Material-4	29.4	29.1	29.1
Material-5	29.1	28.9	28.9
Material-6	29.2	29.0	29.0
Material-7	29.0	28.8	28.8

This is observed that Material 7 can reduce the air temperature to a greater extent compared to other materials. Material 7 was composed of 6.4 mm local tile, 200 mm concrete, and 10 mm plaster. Concrete has suitable properties for thermal mass which absorb excess heat without getting hot. Moreover, if the effects of trees can be incorporated in outdoor weather conditions, the air temperature can be reduced more (up to 1.0^oC) compared to the original weather conditions. Besides, by introducing the effects of lake air temperature can be reduced up to 0.6^oC compared to the original weather condition. In all conditions, air temperature slightly decreases with the increase of ventilation rate.

Table 6.12 Indoor Mean Air Temperature [^oC] in Nighttime Ventilation Schedule, Original epw

Material Types	Ventilation Rates		
	V_0	V_{10}	V_{20}
Material-1	30.4	30.1	30.1
Material-2	30.4	30.1	30.1
Material-3	30.3	30.0	30.0
Material-4	30.4	30.0	29.9
Material-5	30.1	29.8	29.8
Material-6	30.2	29.9	29.9
Material-7	30.0	29.7	29.7

Table 6.13 Indoor Mean Air Temperature [^oC] in Nighttime Ventilation Schedule, Lake epw

Material Types	Ventilation Rates		
	V_0	V_{10}	V_{20}
Material-1	29.8	29.4	29.4
Material-2	29.7	29.4	29.4
Material-3	29.7	29.4	29.3
Material-4	29.8	29.3	29.2
Material-5	29.4	29.2	29.1
Material-6	29.6	29.2	29.2
Material-7	29.3	29.0	29.0

Table 6.14 Indoor Mean Air Temperature [^{o}C] in Nighttime Ventilation Schedule, Tree epw

Material Types	Ventilation Rates		
	V_0	V_{10}	V_{20}
Material-1	29.4	29.0	29.0
Material-2	29.4	29.1	29.1
Material-3	29.3	29.0	29.0
Material-4	29.4	28.9	28.9
Material-5	29.1	28.8	28.8
Material-6	29.2	28.9	28.8
Material-7	29.0	28.7	28.6

Table 6.12-6.14 present the indoor mean air temperature (8:00-17:00 LST) results when the nighttime ventilation schedule was considered in operation along with different construction materials and different outdoor weather conditions including the effects of trees and lakes. Material 7 can reduce air temperature compared to other materials like daytime ventilation scenarios. In addition, the air temperature can be reduced more (up to 1.1^{o}C) compared to the original weather conditions when the effects of trees can be incorporated in outdoor weather conditions. Further, by introducing the effects of lake air temperature can be reduced up to 0.7^{o}C compared to the original weather condition. The air temperature slightly decreases with the increase of ventilation rate in all conditions. Since the nighttime air temperature was comparatively lower than the daytime air temperature, the overall mean air temperature obtained in the nighttime ventilation schedule was found slightly lower than the mean air temperature obtained in the daytime ventilation schedule. Consequently, a little difference (0.1^{o}C) was found of the air temperature reduction between daytime and nighttime ventilation schedule.

6.4.5 Standard Effective Temperature (SET*) Results of Parametric Study

Based on simulation results of indoor air temperature, mean radiant temperature, relative humidity, Standard Effective Temperature (SET*) has been calculated to evaluate the indoor thermal comfort condition. Figures 6.6 and 6.7 show the SET* in different conditions. The SET* has been presented for a typical summer season week in the month of May.

Tukey's honestly significant difference (HSD) test was carried out to identify the best condition for thermal comfort (Figure 6.6 & 6.7). It can be used to find means that are significantly different from each other. Here, SET* have been calculated for seven different construction material of the exterior wall including the cooling effects of trees and lakes and considering daytime and nighttime ventilation schedule. In Figure 6.6 and 6.7 e.g., DM1Or means a combined condition of daytime ventilation schedule, Material 1, and Original weather condition, DM1Tr denotes for daytime ventilation schedule, Material 1, and tree weather condition and DM1La stands for daytime ventilation schedule, Material 1, and lake weather condition. In the same way, NM1Or indicates nighttime ventilation schedule, Material 1, and Original weather condition. In Tukey's Honestly Significant Difference (HSD) test each condition (e.g. DM1Or….DM7Tr) has been ranked (e.g. 'a'….'f', and 'a'….'e') according to the SET* value. In daytime ventilation schedule, Material 1 in 'Original' weather condition possesses the highest SET* value (30.0^{o}C) and ranked as 'a', and Material 7 in 'Tree' weather condition possesses the lowest SET* value (28.5^{o}C) and ranked as 'f'. In nighttime ventilation schedule, Material 1 in 'Original' weather condition possesses the highest SET* value (29.9^{o}C) and ranked as 'a', and Material 7 in 'Tree' weather condition possesses the lowest SET* value (28.4^{o}C) and ranked as 'e'. Thought the values are different, in both case of daytime and nighttime ventilation schedule, Material 7 and effects of trees resulted the lowest SET*. Therefore, using concrete as the construction material of exterior wall and incorporating the effects of trees in the outdoor settings can enhance the indoor thermal comfort condition.

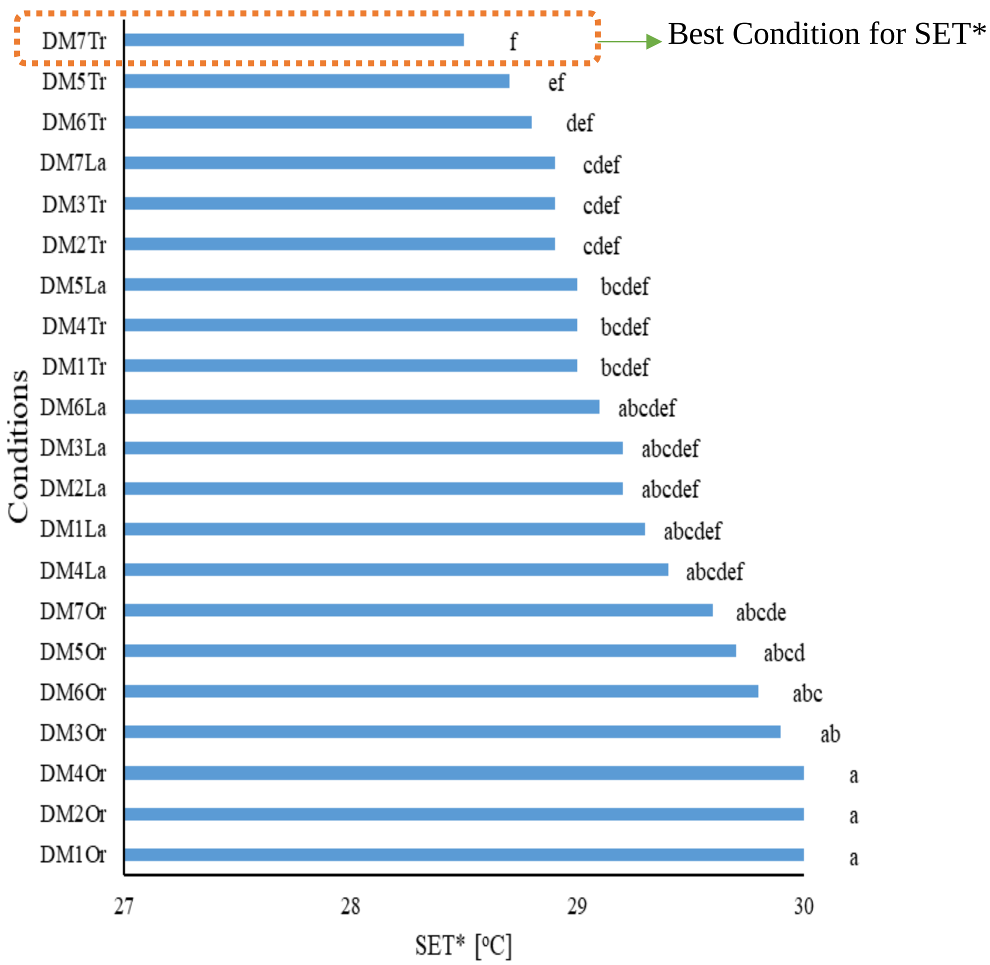


Figure 6.6 SET*, Daytime Ventilation Schedule

The cooling effects of trees and lakes in an outdoor setting are clearly visible in the indoor thermal comfort condition. Change in the exterior wall construction (using concrete as defined in Material 7) and incorporating the tree's influence in an outdoor setting can reduce the SET* up to 1.5°C. Besides, outdoor settings incorporating the influence of the lake with the same design modification (using Material 7) can lower the SET* up to 1.1°C. The SET* values determined in the night ventilation schedule were slightly lower than the SET* values in the daytime ventilation schedule.

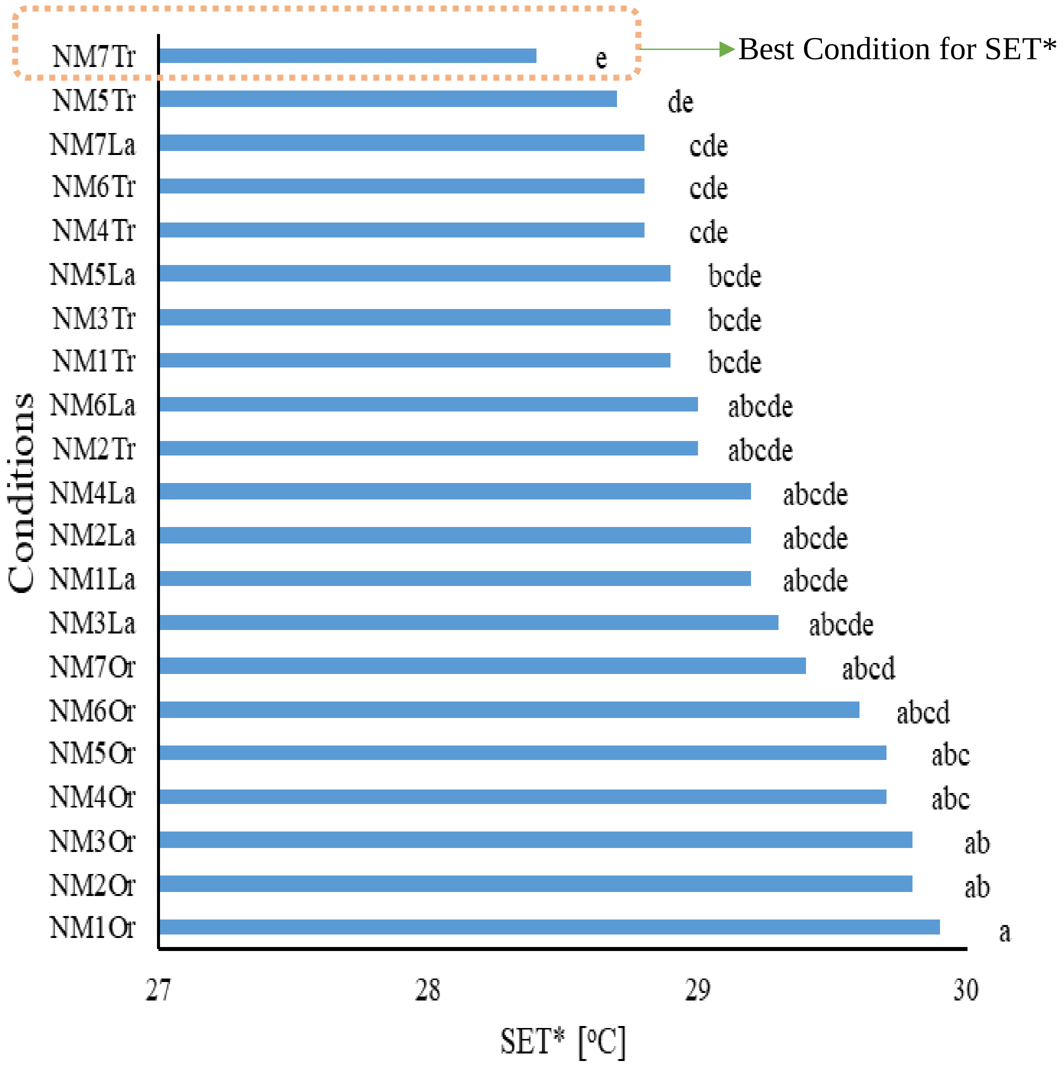


Figure 6.7 SET*, Nighttime Ventilation Schedule

The thermal mass characteristics of concrete are suitable to absorb excess heat without getting hot. Therefore, concrete can be considered as a better construction material for exterior walls. However, the use of concrete and thermal insulation could be a big challenge in Bangladesh. The construction contractors in Bangladesh usually use brick to construct exterior walls to reduce the construction cost. Since the nighttime air temperature is relatively lower than the daytime air temperature, the nighttime ventilation schedule slightly reduces the SET* than the daytime ventilation schedule. However, this reduction is very small and could not act as a night flush out more efficiently. Additionally, this is also very difficult to maintain a nighttime ventilation schedule in the case of an educational building. The combination of modified outdoor environmental settings by tree and lake, using concrete in the construction of the exterior wall, and operating daytime ventilation schedule could reduce the air temperature and SET* and thereby enhance the comfort condition in the university classroom.

6.5 Conclusions

EnergyPlus, an energy analysis, and a thermal load simulation program are used for model calibration and parametric study. Calibration is considered as an important factor in a simulation study. The air temperature and mean radiant temperature were used for results comparison in the process of calibration. Building description regarding the specifications and weather data developed by the Solar and Wind Energy Resource Assessment (SWERA) project was inputted in EnergyPlus and simulation was run. Then the trend of simulation results and measurement results were compared. The results indicated the correspondence between the simulation results and the measurement results. The indoor air temperature from the field measurement was slightly higher (0.7^{o}C) than in the simulation because of insufficient ventilation during measurement. A constant air flow rate can be maintained in simulation and thereby natural ventilation in simulation showed slightly greater performance than in real situations. In addition, the trend of mean radiant temperature in simulation also showed the correspondence with the measured results.

The exterior walls affect the indoor thermal environment. Therefore, a parametric study was conducted to identify the best composition of materials and construction pattern of the exterior walls. Usually, bricks are used in the construction of exterior walls of educational buildings in Bangladesh. In the base case of parametric study, the exterior wall was composed of plaster, brick, and plaster. Results of the parametric study indicated that using concrete instead of brick could lower the air temperature. Depending on layer thickness, concrete can reduce air temperature up to 0.4^{o}C. Concrete has suitable properties for thermal mass which absorb excess heat without getting hot. Therefore, concrete can be considered as a better construction material for exterior walls.

To examine the influence of outdoor environmental settings on the indoor environment, simulation was run through original EnergyPlus weather data (Original epw), configured weather data from tree (Tree epw) and lake (Lake epw) cases. The influence of tree and lake on the indoor thermal environment were identified. If the effects of trees can be incorporated in outdoor weather conditions, the indoor air temperature can be reduced up to 1.0^{o}C compared to the original weather conditions while operating daytime ventilation schedule. Further, by introducing the effects of lake, the indoor air temperature can be reduced up to 0.7^{o}C compared to the original weather condition. The air temperature slightly decreases with the increase of ventilation rate in all conditions.

Finally, the combined impacts of design modification, outdoor environmental settings, and ventilation schedule were examined. Using concrete instead of the brick construction of the exterior wall (as defined in Material 7) along with incorporating the tree's influence in an outdoor setting can reduce the SET* up to 1.5^{o}C. Moreover, outdoor setting incorporating the influence of lake with the same design modification (using Material 7) can lower the SET* up to 1.1^{o}C. The nighttime ventilation schedule has a marginal impact on the SET* reduction and this is also very difficult to operate nighttime ventilation in educational buildings. Therefore, daytime ventilation can be considered a suitable ventilation schedule.

Chapter 7

Conclusions

The conclusion of this dissertation will be presented along with guideline for design considerations for university spaces in tropical climate of Dhaka, Bangladesh. For the future study, further recommendations are also placed.

7.1 Conclusions

The world is becoming predominantly urban over the last century. In the process of rapid urbanization, the land use and land cover changes, air pollution, and a higher demand for energy consumption situations are becoming obvious consequences. The low reflectivity of the urban surface combined with a high density of construction results in an accumulation of heat in the urban environment and consequently increases discomfort. In Bangladesh, the rate of urbanization is very high. Moreover, the demographic and economic changes increase the demand for university education dramatically over the past two decades. Consequently, enrollment in universities has been growing rapidly along with the number of universities increment. It is predicted that the demand for tertiary education will continue to grow as the share of youth population with increases. Teaching and learning related activities are affected directly by the thermal environment. To attain maximum performance from the students and faculty members, promoting thermal comfort design guidelines in university spaces is inevitable.

This study was conducted by field measurement-based investigation and computer program-based simulation. The field measurement was carried out in the typical hot summer days between May and June in different indoor and outdoor university spaces. Field measurement was conducted on daytime only, to measure air temperature, relative humidity, globe temperature, air velocity, solar irradiation. Comfort index (SET*) has been calculated based on measurement weather data along with human factor e.g., metabolic rate and clothing insulation. The filed measurement results indicate that the indoor weather parameters e.g., air temperature, relative humidity approach in a stable way as the time progresses. The outdoor weather parameters, on contrary, fluctuated in a greater extent. The outdoor air temperature and air velocity were recorded higher than their indoor counterparts.

The indoor thermal environments correspond to those surrounding outdoor weather. For example, the outdoor air temperature of more tree area was found lower than the air temperature of area with less tree. In response to the outdoor condition, air temperature in the classroom surrounded by more tree area was found lower than in the classroom surrounded by less tree area. Similar measurement was carried out to detect the air temperature difference in lakeside and non-lakeside classrooms. The outdoor air temperature near the lakeside classroom was found lower than the outdoor space of non-lakeside classroom. However, the indoor air temperature of the lakeside classroom was found slightly higher than non-lakeside classroom. The lakeside classroom is located on the top floor of the building and exposed more to the sunlight and thus slightly increased air temperature was found. The non-lakeside classroom, on the other hand, is not located on the top floor and exposed less to the sunlight. From the measurement results the effects of lakeside outdoor environment on the indoor thermal environment was not clearly identified. Therefore, further investigation is required to identify effect of lake on indoor thermal environment.

A considerable impact of the weather parameters especially air temperature and air velocity has been observed on the comfort index. As a result, the outdoor SET* values fluctuate more than the indoor SET*. Since the outdoor air temperature was higher, consequently the outdoor SET* trend was also found higher than the indoor SET* trend. Likewise weather parameters, the indoor SET* trend showed the correspondence with the outdoor SET* trend. The outdoor and indoor SET* values of Classroom surrounded by more trees were lower than Classroom surrounded by less tree. Providing solar protection through shading, absorbing solar radiation, affecting air movement, and evapotranspiration processes trees are capable to lower down the air temperature considerably. In addition, lake can contribute to the reduction of outdoor air temperature compared to the non-lakeside space. Concurrently, the mean SET* values near the lake is lower than the non-lakeside space. The high thermal capacity of the lake and evaporation process reduced the air temperature and thereby dropped the SET* values down at the surrounding space of lakeside classroom. In field measurement the lakeside classroom was located on the top floor of a three storied building, which was exposed more to solar radiation. The non-lakeside classroom was not located on the top floor and thereby air temperature was found slightly lower than in lakeside classroom. Thus, in comparing with non-lakeside indoor air temperature and comfort index value slightly different scenario was observed. The overall SET* values indicate the comfort condition in indoor and outdoor are away from the standard comfort zone. Therefore, this is necessary to focus on air temperature reduction and air velocity augmentation to achieve desirable thermal environment.

EnergyPlus is used for model calibration and parametric study. In simulation study calibration is considered as an important factor. Air temperature and mean radiant temperature were used for results comparison in the process of calibration. Building description regarding the specifications and weather data developed by the Solar and Wind Energy Resource Assessment (SWERA) project was inputted in EnergyPlus. The trend of simulation results and measurement results were compared. The results indicated the correspondence between the simulation results and the measurement results. In simulation results, the indoor air temperature was found slightly lower than the measured results. The indoor air temperature from the field measurement was slightly higher than in the simulation because of insufficient ventilation during measurement. A constant air flow rate can be maintained in simulation and thereby natural ventilation in simulation showed slightly greater performance than in real situation. In addition, the trend of mean radiant temperature in simulation also showed the correspondence with the measured results.

The exterior walls affect the indoor thermal environment. Therefore, parametric study was conducted to identify the best composition of materials and construction pattern of exterior wall. In the base case, the exterior wall was composed of plaster, brick, and plaster. Results of parametric study indicated that using concrete instead of brick could lower the indoor air temperature. Depending on layer thickness, concrete can reduce the indoor air temperature.

To examine the influence of outdoor environmental settings on indoor environment, simulation was run through original EnergyPlus weather data (Original epw), configured weather data from tree (Tree epw) and lake (Lake epw) cases. The influence of tree and lake on the indoor thermal environment were identified. If the effects of tree can be incorporated in outdoor weather condition, the indoor air temperature can be reduced more compared to the original weather conditions. Further, by introducing the effects of lake, the indoor air temperature can be reduced compared to the original weather condition. The indoor air temperature slightly decreases with the increase of ventilation rate in all conditions when nighttime ventilation schedule was in operation.

Lastly, the collective impacts of design modification, outdoor environmental settings, and ventilation schedule were examined. Using concrete instead of brick construction of exterior wall along with incorporating tree’s influence in outdoor setting can reduce the SET*. Moreover, outdoor setting incorporating the influence of lake with same design modification can also lower the SET*. The nighttime ventilation schedule has marginal impact on the SET* reduction and this is also very difficult to operate nighttime ventilation in educational buildings.

The presence of tree and lake in the outdoor space can improve the outdoor and indoor thermal environment. Therefore, integration of design modification and incorporating tree and lake in outdoor environmental setting in enhancing indoor thermal environment presented in this dissertation can be used as an initial guideline for the city planners, designers, and architects to enhance thermal environment and comfort in university spaces.

7.2 Further Recommendations

This study attempted to enhance the thermal comfort in university classroom in the tropical climate of Dhaka, Bangladesh. Thermal properties of the building envelop should be studied in more detail. Additionally, solar reflectance of the exterior wall by changing building’s color should be analyzed.

Outdoor environmental settings should be analyzed in detail. Further study on incorporating the influence of tree more effectively species of tree, and plantation pattern should be considered. Lake size, distance between lake and building, and location should be considered to examine the effects of lake on indoor thermal environment.

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1. Thermal Comfort Investigation Based Design Considerations for the Tropical Studio Type Classroom, International Journal of Sustainable Development and Planning, Vol.15, No. 8, December, 2020, pp. 1179-1185 (Published).

2. Analyzing the effect of Water body on the Thermal Environment and Comfort at Indoor and Outdoor Spaces in Tropical University Campus, International Journal of Environmental Science and Development, Vol.12, No. 10, October, 2021 (Accepted).