

## Research Article

# Effects of Urban Configuration on Human Thermal Conditions in a Typical Tropical African Coastal City

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A long-term simulation of urban climate was done using the easily available long-term meteorological data from a nearby synoptic station in a tropical coastal city of Dar es Salaam, Tanzania. The study aimed at determining the effects of buildings' height and street orientations on human thermal conditions at pedestrian level. The urban configuration was represented by a typical urban street and a small urban park near the seaside. The simulations were conducted in the microscale applied climate model of RayMan, and results were interpreted in terms of the thermal comfort parameters of mean radiant ( $T_{mrt}$ ) and physiologically equivalent (PET) temperatures. PET values, high as 34°C, are observed to prevail during the afternoons especially in the east-west oriented streets, and buildings' height of 5 m has less effect on the thermal comfort. The optimal reduction of  $T_{mrt}$  and PET values for pedestrians was observed on the nearly north-south reoriented streets and with increased buildings' height especially close to 100 m. Likewise, buildings close to the park enhance comfort conditions in the park through additional shadow. The study provides design implications and management of open spaces like urban parks in cities for the sake of improving thermal comfort conditions for pedestrians.

## 1. Introduction

Dar es Salaam is a hot, humid tropical city situated along the Tanzanian coast on the Western Indian Ocean coast. It enjoys the sea-land breezes system which is observed to be more organised during the months of March, April, September, and October [1, 2]. On the other hand, sultriness is not uncommon particularly during the December–February (DJF) season. Such sultry conditions bring an undesirable thermal discomfort especially to pedestrians and street vendors. Most biometeorological studies done elsewhere have revealed the effects of street orientation and height to width ratio on the variation of local thermal comfort at an urban canyon level [3–6].

Although the human thermal comfort is influenced by four meteorological parameters of air temperature, humidity, wind speed, and radiation flux (usually quantified in terms of mean radiant temperature), it is the wind speed and mean radiant temperature which can be significantly varied by

changing the street orientation and height to width ratio [7]. A past urban climate research in Dar es Salaam has suggested that the observed sea-land breeze effect could improve the thermal comfort at high ground places in the city like at the university of Dar es Salaam campus which is about 12 km to the west from the city centre [1]. Moreover, various methods have been applied elsewhere in order to deepen the understanding of the effect of street geometry and orientation on urban thermal comfort especially at pedestrian level. For instance, from the field-measurements in an east-west urban canyon during cloudless summer weather in 2003, it was found that thermal stress is mostly attributable to solar exposure, and the study suggested further field investigations to be done in other locations and climatic conditions in order to verify the generality of such thermal observations in street canyons [3].

In Fez, Morocco, measurements were carried out during the hot summer and cool winter seasons where the deep canyons were found considerably cooler in day than

the shallow canyons [8]. Effects of urban configuration on urban thermal climate have also been recently explored through series of field measurements in many cities including Tokyo, Japan [9] Athens, Greece [4] Constantine [5], Colombo [10, 11]. In some of the cities situated within the coastal environments, influence of sea breezes on urban thermal climate was also investigated [10, 12, 13].

Likewise, numerical simulation also offers a valuable method to understanding the effects of urban geometry and street orientation. In Ghardaia, Algeria, numerical simulations were done using the three-dimensional numerical model, ENVI-met, for a typical summer day, and results showed contrasting patterns of thermal comfort between shallow and deep urban streets as well as between various orientations [6]. In studying the impact of street geometry on ambient temperatures and on daytime pedestrian comfort levels, two approaches involving field measurements and urban climate simulations using the ENVI-met were carried out in downtown of Curitiba, Brazil [14]. Having observed that maximum daily temperature within street canyons in Colombo, Sri Lanka, decreases with increasing height to width ( $H/W$ ) ratio and that sea breezes exert a cooling effect, simulations done in ENVI-met model were initiated by data obtained from a synoptic weather station located at the airport (approximately 24 km north of the measurement location) for the purpose of understanding the effect of different urban design options on air and surface temperatures, as well as on outdoor thermal comfort [15]. Similarly, long-term thermal comfort at the University Campus in Taiwan was predicted by using long-term meteorological data collected from a nearby station, and simulations were performed in RayMan model [7]. This suggests that with modern advances in urban climatology especially through continuous improvement on the available microscale models, assessment of thermal conditions in urban places could then be sufficiently studied where simulations could deliver helpful results. Besides, most field studies examining outdoor thermal comfort merely clarify characteristics measured on a particular day; hence, such studies may not represent annual thermal conditions accurately.

Due to its coastal location and proximity to the equator, Dar es Salaam seems to be a perfect location of understanding the effects of urban geometry on human thermal comfort at pedestrian level in the low latitudes. Long-term analysis of urban thermal climate in Dar es Salaam is therefore of paramount importance in understanding the tropical urban climate in a typical African city.

The current study, therefore aimed at quantifying the effects of the buildings' height and orientation on radiation fluxes in a typical urban canyon and an urban park in a tropical African city. In order to optimise thermal comfort through modified urban configurations, human thermal index of physiologically equivalent temperature (PET) was used in visualizing the changes in terms of thermal comfort classes after every modification. Simulations were performed using the microscale model of RayMan [16, 17]. The model is reputed to be easy to use. Recent research done in a midlatitude city found that RayMan can even deliver more accurate results at high sun elevations [18], and this underpins it as

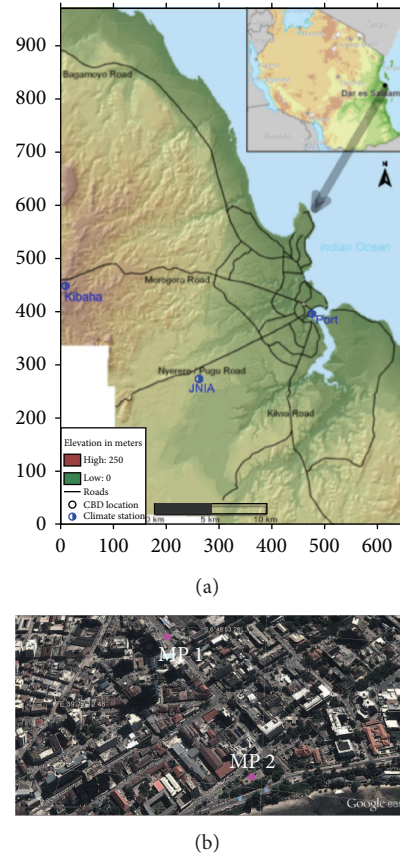


FIGURE 1: (a) Location of measurement stations and area of study. Source: modified from Hill and Lindner (2010). (b) A satellite picture as obtained from Google Earth, locating the simulation points, MP1 (typical urban street) and MP2 (urban park), in a part of Dar es Salaam city, Tanzania.

an ideal microscale model to study urban climate in the low latitude cities including Dar es Salaam where, as elsewhere in the world, the afternoons are usually the most thermal stressful times [1, 2]. Simulating the optimal configurations for thermal comfort in Dar es Salaam is of utmost importance in advancing the science of urban climate in low latitudes and urban planning of cities in developing countries. Dar es Salaam is an important economic centre in eastern Africa due to its harbour services, and it has recently been observed to expand rapidly. Better understanding of its urban climate is significant for its future urban planning and well-being of the increasing population.

## 2. Methods

Dar es Salaam (Figure 1(a)) is located at  $6^{\circ}51'S$ ,  $39^{\circ}18'E$  along the south western coast of the Indian ocean, covering an area of  $1350 \text{ km}^2$  of which about  $1000 \text{ km}^2$  is a land area [19, 20]. Dar es Salaam is generally a lowland area with its altitude ranging from the sea level at the coast to an approximately 250 m in the south-west along the Pugu hills situated about 25 km from the city centre [21]. The climate is typically hot-humid, referred to as *tropical wet/dry climate (Aw)* according

to the Köppen classification system [22, 23]. The climate is mainly influenced by the northeast monsoon which prevails from March to October and the southeast monsoon between October and March [19]. This is in response to the passage of the Intertropical convergence zone (ITCZ). Local winds are generally high up to 13 m/s during the afternoons particularly from August to November.

Usually, the relative humidity in Dar es Salaam ranges between 67 and 96% in a year, and the annual rainfall is about 1050 mm with peaks in April and December. April is however the wettest month, and the rain seasons are usually described as short rains (October–December season) with an average of 75 to 100 mm and long rains (March–May season) with a monthly average of 150 to 300 mm of rainfall [24]. The mean annual air temperature is about 30°C with a slight seasonal change due to its proximity to the equator. The mean daily sunshine duration is about 10–12 hours.

The study area comprised of two urban resort places (Figure 1(b)). The first area (MP1) is along the typical street (width of 24.5 m) in the downtown area of Dar es Salaam. One side of the street there is a tall building of 21 storeys (about 93 m high), and the other side is a waiting area for boarding public transport. The second area of simulation (MP2) is on a small urban park (locally called as a Posta garden) overlooking the sea to the south. It also serves as the bus waiting and recreation place. The street is originally orientated in a northwest-southeast direction (i.e., about 45° from the north in an anticlockwise direction) while the park takes the triangle-like shape measuring 156 m × 140 m × 60 m with its hypotenuse facing the sea. There are few trees of mainly Ashoka type along the street whereas the park has many trees with different species, but notably the leaf trees of Neem species, grass, and a concrete floor at the centre. Although the park overlooks the sea, the presence of two lines of trees may act as an obstacle to the sea breezes at low levels or near the ground level. Simulations were therefore done by rotating the orientation every 15° and by increasing the buildings' height by 5 m up to 50 m, and 100 m was taken as the maximum height of the current highest building in the city.

The input meteorological data used for the long-term simulation were based on the available meteorological data collected at a synoptic station located at the Julius Nyerere International Airport (JNIA) (see Figure 1(a)). These data were from the year 2001 to 2012. The airport station usually does meteorological observations at every synoptic hour. However, the available data used in this study had a three-hour frequency period, with observation times at 0 LST (local standard time), 3 LST, 6 LST, 9 LST, 12 LST, 15 LST, 18 LST, and 21 LST. These include air temperature, wind speed, relative humidity, and amount of cloud cover. Cloud cover was used to estimate the radiation flux as there are only daily measurements of radiation at the synoptic station. The airport datasets were used on the assumption that they form a continuous long-term dataset as required in long-term climatic analysis, unlike the datasets from the other two stations. The urban effect at MP1 and MP2 locations was considered to affect the wind speed which was then

TABLE 1: Climate measuring stations in Dar es Salaam.

| Meteorological station | Grid reference   | Altitude (m) | Approximate distance to area of study (km) |
|------------------------|------------------|--------------|--|
| JNIA                   | 06°52'S, 39°12'E | 53.0         | 11.2                                       |
| Port                   | 06°50'S, 39°18'E | 18.0         | 0.8  |
| Kibaha                 | 06°50'S, 38°58'E | 167.0        | 35.2                                       |

Source: Tanzania meteorological agency.

estimated from the readings at the airport station using equation provided in [25] and applied in [26]:

$$ws_{1.1} = ws_h \left( \frac{1.1}{h} \right)^\alpha, \quad \alpha = 0.12z_0 + 0.18, \quad (1)$$

where  $ws_h$  is the wind speed ( $ms^{-1}$ ) at a height of  $h$  (10 m),  $\alpha$  is an empirical exponent that depends on the surface roughness, and  $z_0$  is the roughness length. Due to slight differences in terrain features at MP1 (a densely built-up city area) and MP2 (partly wooded areas with buildings and open to sea),  $z_0$  were taken to be 1.5 and 1.3, respectively, though both areas are within the inner city.

Additional meteorological datasets of air temperature (including maximum and minimum) and relative humidity were also obtained from other two stations located at the harbour (Port) and at the Kibaha Sugarcane Research Institute (Kibaha) (see Figure 1(a) and Table 1). The air temperature datasets from the two stations were from the year 2001 to 2011, whereas relative humidity data spanned for the period March–September 2005 was only collected at the Port station. These additional datasets were compared with the corresponding datasets from the airport station in order to establish the rationale of using long-term synoptic data to simulate urban bioclimatic conditions. Comparison between the weather elements from the three weather stations was examined using the rank correlation of Kendall tau correlation at a 0.05 significance level. The Kendall tau is a bivariate measure of correlation/association usually used for the rank-order data [27].

The simulated bioclimatic conditions at pedestrian level were interpreted using PET and  $T_{mrt}$ . PET evaluates the thermal conditions in a human physiological manner and uses a commonly known unit of degree Celsius. PET is defined as the air temperature at which the human energy budget for the assumed indoor conditions is balanced by the same skin temperature and sweat rate as under the actual complex outdoor conditions to be assessed [28–30]. On the other hand, the mean radiant temperature is defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual nonuniform enclosure [31].  $T_{mrt}$  is one of the meteorological parameters that govern human thermal energy balance hence affecting the human thermal comfort [32].

As the aim of the study was to determine the optimal urban configuration for the urban thermal comfort in Dar es Salaam at pedestrian level, long-term simulation would give reliable and comprehensive information as opposed to short

field measurements. Field studies examine outdoor thermal comfort that merely expound characteristics measured on a particular day and would not accurately represent the annual thermal conditions. Besides, the lack of urban meteorological stations with continuous measurements in many tropical cities including Dar es Salaam lead to many urban climate studies in such cities to rely on the easily available long-term meteorological data from nearby stations [7, 15, 33–35]. For instance, climatic changes in temperature conditions in Nairobi city were investigated using data collected from weather stations situated about 4 kilometres from the city centre [33], and in Taiwan, long-term thermal environment was simulated using meteorological data of a 10-year period collected from a nearby station [7]. However, altitude is acknowledged as a determinant factor for the spatial variation of weather and climate, and winds are experienced to decrease in urban areas [36]. Taking into consideration such observations, variation of weather in Dar es Salaam due to altitude could be assumed insignificant as the synoptic station lies at an altitude of 53 m above sea level while the city centre is at about 11 m above sea level. Theoretically, air temperature varies by  $0.6^{\circ}\text{C}$  for every 100 m high. Furthermore, mean climatic conditions of Dar es Salaam are defined using data from the airport station.

The assumptions that guided the use of the available synoptic meteorological data as input in the simulations thus base on the fact that Dar es Salaam lies within the coastal lowland terrain, and a weather change due to altitude is insignificant within few horizontal distances. A robust and plausible long-term urban thermal characteristic can be attained by using long-term and continuous meteorological data. Although differences exist in some atmospheric parameters between the simulation points in the city and the synoptic weather station, the attributed changes in thermal indices generated by the simulation model are relatively small and can be neglected. Therefore, the simulated results provide a precise representation of the thermal conditions within the city environment.

### 3. Results and Discussion

**3.1. Local Urban Micrometeorological Variations.** The intraurban variation of local meteorological conditions in Dar es Salaam was investigated in order to determine to what extent does the local meteorological conditions change in spatial and temporal scales. Analysis was done only in terms of relative humidity and air temperature due to availability of these meteorological parameters in the three weather stations. Spatial variability in cloud cover could be understood to be within the allowable limits as the observation at the synoptic station is considered to span a horizontal distance of nearly 30 km from the observation point for the horizontal visibility and consequently cloud cover. This analysis was of course considered necessary and of utmost importance to understand the variability of the local weather, and hence, how reliable can the weather parameters at the synoptic weather station be considered representative of the city's climate. Further, variability analysis of weather parameters

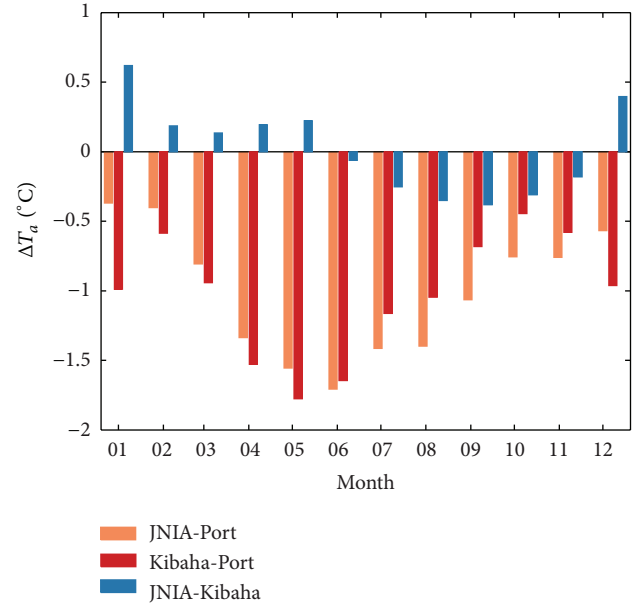


FIGURE 2: Intraurban air temperature differences as depicted by the long-term mean monthly differences between the three weather stations.

was also considered as an important step to establish a rationale of using the meteorological data from the synoptic station as the representative input parameter in the long-term urban climate simulation.

The results, therefore, suggested that the variation of the local micrometeorological conditions in Dar es Salaam could be highly influenced by its proximity to the sea. Places close to the sea could be slightly warmer than those far away from the sea as suggested by the analysis of air temperature from the three stations. Figure 2 depicts the long-term mean monthly air temperature differences ( $\Delta T_a$ ) where air temperature at the Port station could be on average  $1.5^{\circ}\text{C}$  or higher than the readings at the airport and Kibaha stations. The monthly mean air temperature differences between JNIA and Port varied from  $-0.4^{\circ}\text{C}$  in February to  $-1.7^{\circ}\text{C}$  in June and between Port and Kibaha ranged from  $0.3^{\circ}\text{C}$  in October to  $1.8^{\circ}\text{C}$  in May. Between JNIA and Kibaha, the intraurban monthly mean air temperature differences were up to  $0.6^{\circ}\text{C}$  from December to May, warm at JNIA and cold by nearly  $0.5^{\circ}\text{C}$  during June–November season. The intraurban air temperature differences were observed to be more consistent in terms of the mean daily air temperatures in a sense that it is warmer near the seaside (Port station) than inland of the coast (see Figure 2).

The relationship between the evolutions of temperature profiles among the three measuring stations as determined by the Kendall tau coefficient was found to be as low as 0.25 and 0.27 between the maximum air temperature at the Port and that of other stations, respectively (Table 2). On the contrary, the correlation coefficients for the mean and minimum air temperature between the three stations was high as 0.6 suggesting a similar evolution of temperature at the stations. Usually, the maximum temperature is reached at 15 LST

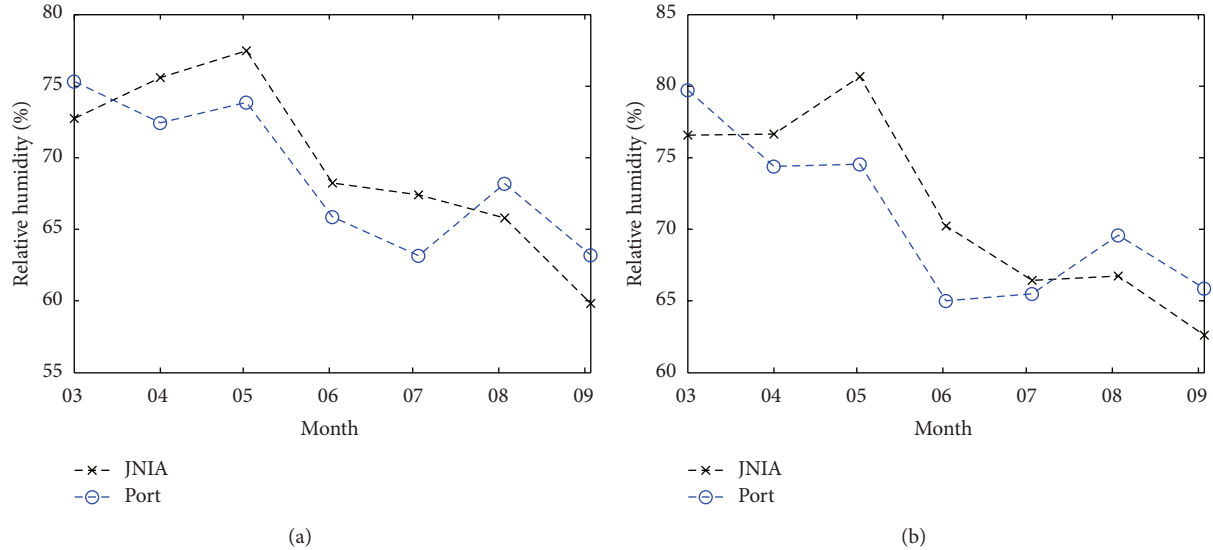


FIGURE 3: Mean monthly relative humidity at JNIA and Port (a) and its corresponding mean relative humidity at 15 LST (lowest relative humidity for the day) (b), for the period March–September 2005.

TABLE 2: Kendall’s tau correlation coefficients at a significant level of 0.05 for intra-urban temperature and relative humidity differences between the three stations.

|               | JNIA-Port | Kibaha-Port | JNIA-Kibaha |
|---------------|-----------|-------------|-------------|
| $T_a$ maximum | 0.25      | 0.27        | 0.72        |
| $T_a$ minimum | 0.87      | 0.86        | 0.87        |
| $T_a$ mean    | 0.70      | 0.60        | 0.67        |
| RH mean       | 0.49      | —           | —           |
| RH at 15 LST  | 0.43      | —           | —           |

where the surface receives much of the solar insolation. The low correlation coefficients between the seaside station and the inland stations during the maximum temperature could be explained by the differences in terrain at the measuring stations. While Port is near to the sea, terrain features at the inland stations is mostly consisted by green vegetation, usually short grass at the airport (JNIA) and scattered trees at Kibaha. It could be suggested that the differences in thermal capacity between the mostly vegetated terrain station and the station near the large water body is pronounced during the daytime. Other studies also found a trend towards a greater difference between annual mean of daily maximum and that of minimum temperatures from the coast to inland stations [37].

Relative humidity is always high along the eastern Africa coast, but our analysis for relative humidity was limited by availability of data in Dar es Salaam area. Although two of the stations (JNIA and Port) can do observation of relative humidity, available data at Port station were limited to six months of the year 2005. This cannot give a conclusive spatial distribution of relative humidity in Dar es Salaam. With such shortcomings, the current analysis, however, surprisingly indicated that relative humidity is slightly higher at the airport station than at a seaside station especially from April

to July (Figure 3). The significant correlation coefficients between readings of relative humidity at the port and the airport stations for the mean monthly and at 15 LST (time of lowest relative humidity) are given in Table 2. The relative humidity climatology of Dar es Salaam as observed from previous studies indicates that relative humidity along the coast usually reach it daily maximum during the night at 90–95% throughout the year, and greater variations are experienced during the daily minimum period at 15 LST [37]. While the seaside station is very close to the city and despite the presence of a large water body, relative humidity readings can as well be influenced by the impervious surface of the urban on the other side. The airport station is well within a short-grass vegetation area. Furthermore, the months of April and May are usually rainy months in Dar es Salaam, and perhaps the proportion difference in terrain features and rain events can influence high humidity in many places not necessarily being close to the sea. However, a good picture of intraurban relative humidity variation in Dar es Salaam could be comprehensive with more datasets with good spatial resolution.

3.2. *Simulation Results in the Street.* The simulations of varying the street orientation and height of buildings were done at two popular urban places in Dar es Salaam for a purpose of quantifying the effects of street orientation and buildings’ height on the human thermal comfort at pedestrian level. This section therefore describes the results of the simulation performed at the street and at the urban park.

In its original orientation of a northwest-southeast direction and settings of one side with tall buildings, pedestrians at the street can experience thermal stress during the afternoons. The temporal distribution of  $T_{mrt}$  as depicted in Figure 4 indicates high values of about  $45^\circ\text{C}$  occurring at around 12 LST from the end of November through

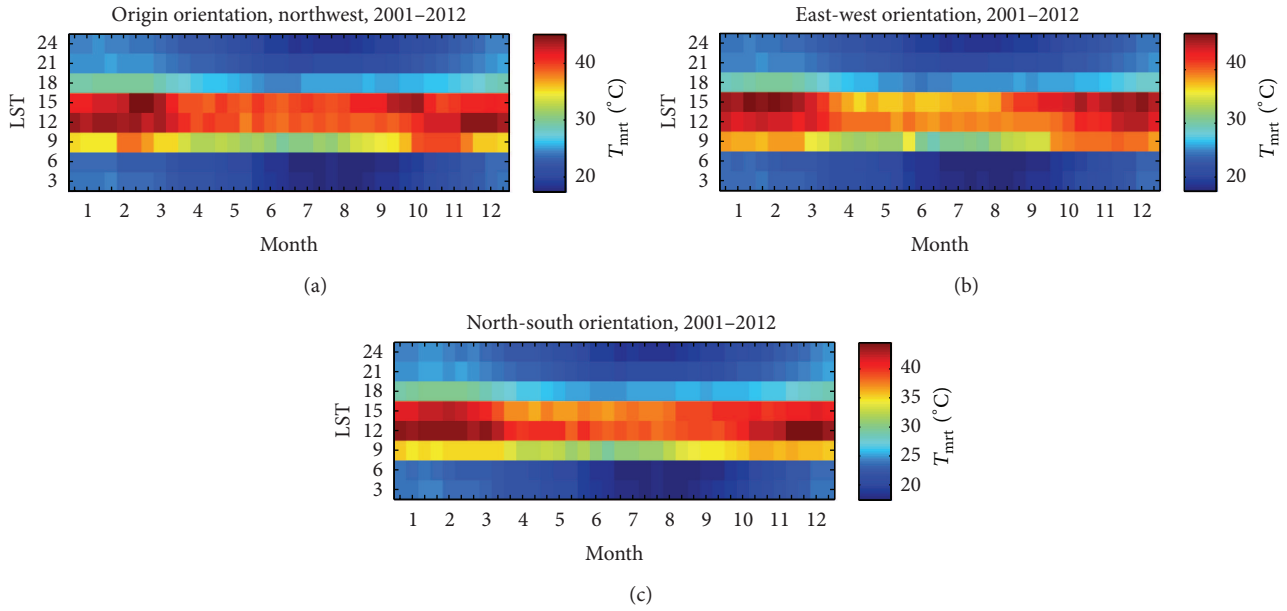


FIGURE 4: The temporal distribution of  $T_{mrt}$  at the urban street in its origin orientation of a northwest-southeast direction (a), east-west orientation ( $225^\circ$ ) (b) and north-south orientation ( $315^\circ$ ) (c).

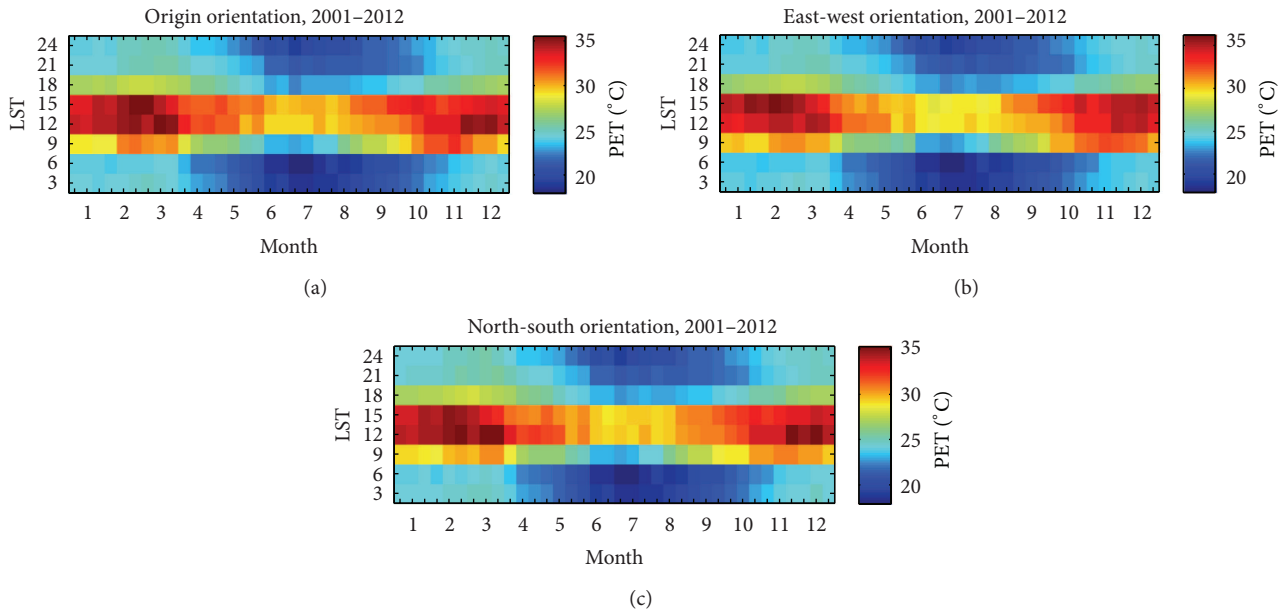


FIGURE 5: The temporal distribution of thermal comfort conditions in terms of PET index at the urban street in its origin orientation of a northwest-southeast direction (a), east-west orientation ( $225^\circ$ ) (b), and north-south orientation ( $315^\circ$ ) (c), suggesting a high prevalence of human thermal stress between 12 and 15 LST particularly from late October to early April.

the beginning of January as well in March. When reoriented in the west-east direction, the highest values of  $T_{mrt}$  above  $45^\circ\text{C}$  became prevalent at 15 LST in October and from late January to early March while in the north-south reorientation, high values of  $T_{mrt}$  of more than  $45^\circ\text{C}$  prevailed at noon time from late November to early March.

The corresponding situation in terms of human thermal comfort was analysed using PET index and depicted in Figure 5. The temporal distribution then indicated that high

value of PET as  $34^\circ\text{C}$  was prevalent between 12 and 15 LST in the months of February, March, November, and December. Further, in an east-west reorientation, high PET values of about  $34^\circ\text{C}$  could frequently occur between 12 and 15 LST in March and November whereas in the north-south reorientation similar high values would be experienced in February, March, November, and December in the same hours of the day. The same period was also identified in the earlier studies as the most thermal stress period in Dar es Salaam

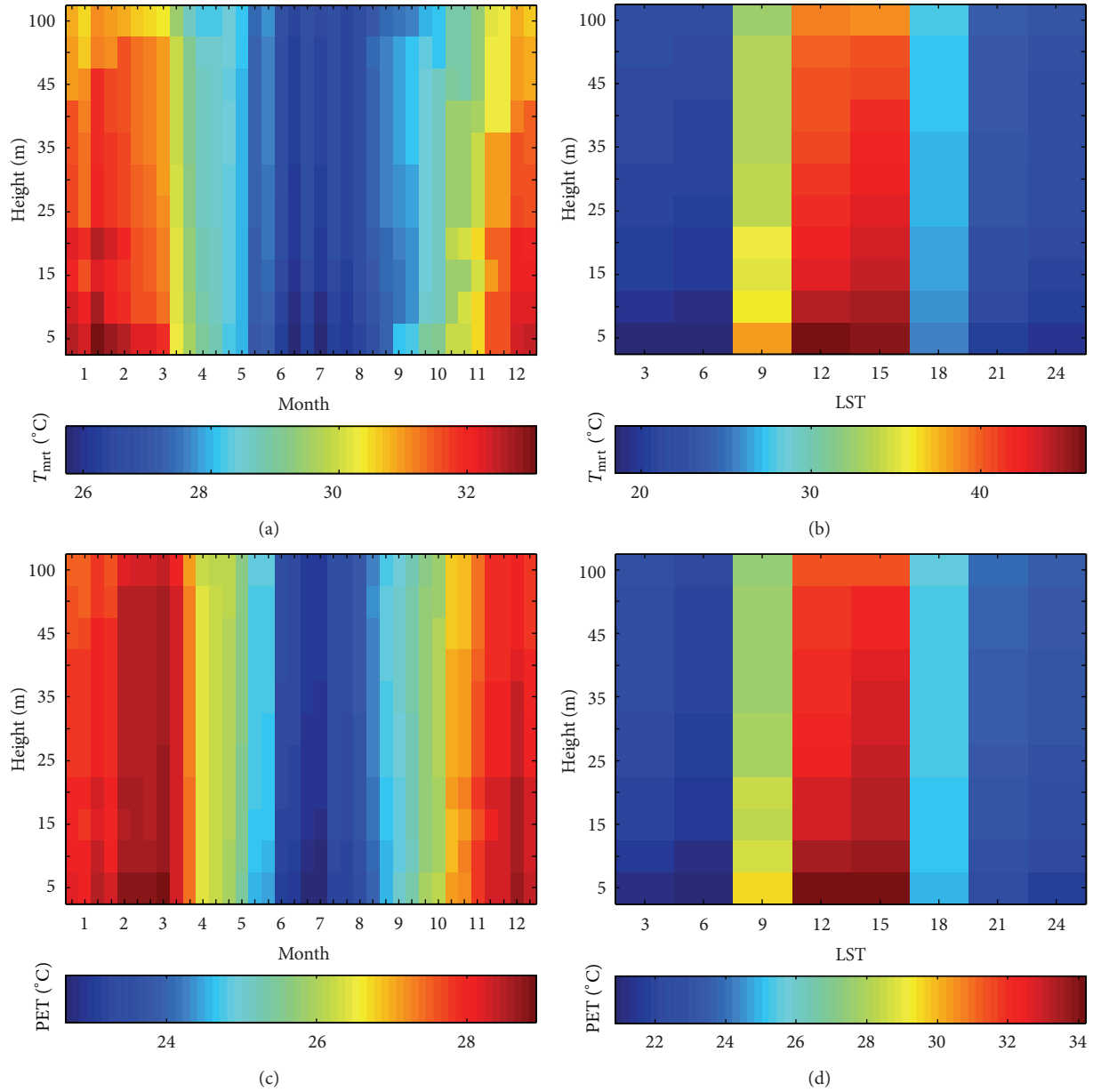


FIGURE 6: Effects of increasing buildings' height on the temporal distribution of  $T_{mrt}$  at the urban street as depicted in the annual cycle (a) and the diurnal cycle (b). The corresponding thermal comfort distribution is shown in terms of PET index ((c) and (d)).

even without considering urban obstacles in calculating the thermal indices [1, 2]. Thus, in order to visualize the thermal comfort characteristics in Dar es Salaam, an idealized urban canyon was considered in further analysis.

An idealized urban canyon with equal heights of buildings on each side was then formulated based on the settings of the original street, and simulations were done by varying the orientation and height of buildings. It is important to note that the new city master plan strategize on densification of the central business district (CBD) of Dar es Salaam through erecting buildings of more than 10 storeys while leaving most of the streets' widths unchanged. Results in this setting are described in Figures 6 and 7 in terms of the annual and

diurnal cycles of evolution of  $T_{mrt}$  and its corresponding thermal comfort condition in terms of PET index.

From Figure 6, effect of buildings' height is described in terms of the annual and diurnal distribution of  $T_{mrt}$  ((a) and (b)) and its corresponding PET index ((c) and (d)). It could then be evidently observed that a significant reduction of  $T_{mrt}$  and PET values just at the buildings' height of 20 m can be attained and more reduction at the height of 100 m. Whereas, effect of street orientation is illustrated by keeping the buildings at a height of 5 m (Figures 7(a) and 7(b)) and at a height of 25 m. Although significant differences could not be easily discerned at the 5 m buildings' height (Figures 7(a) and 7(b)), it is evident that street orientation particularly on

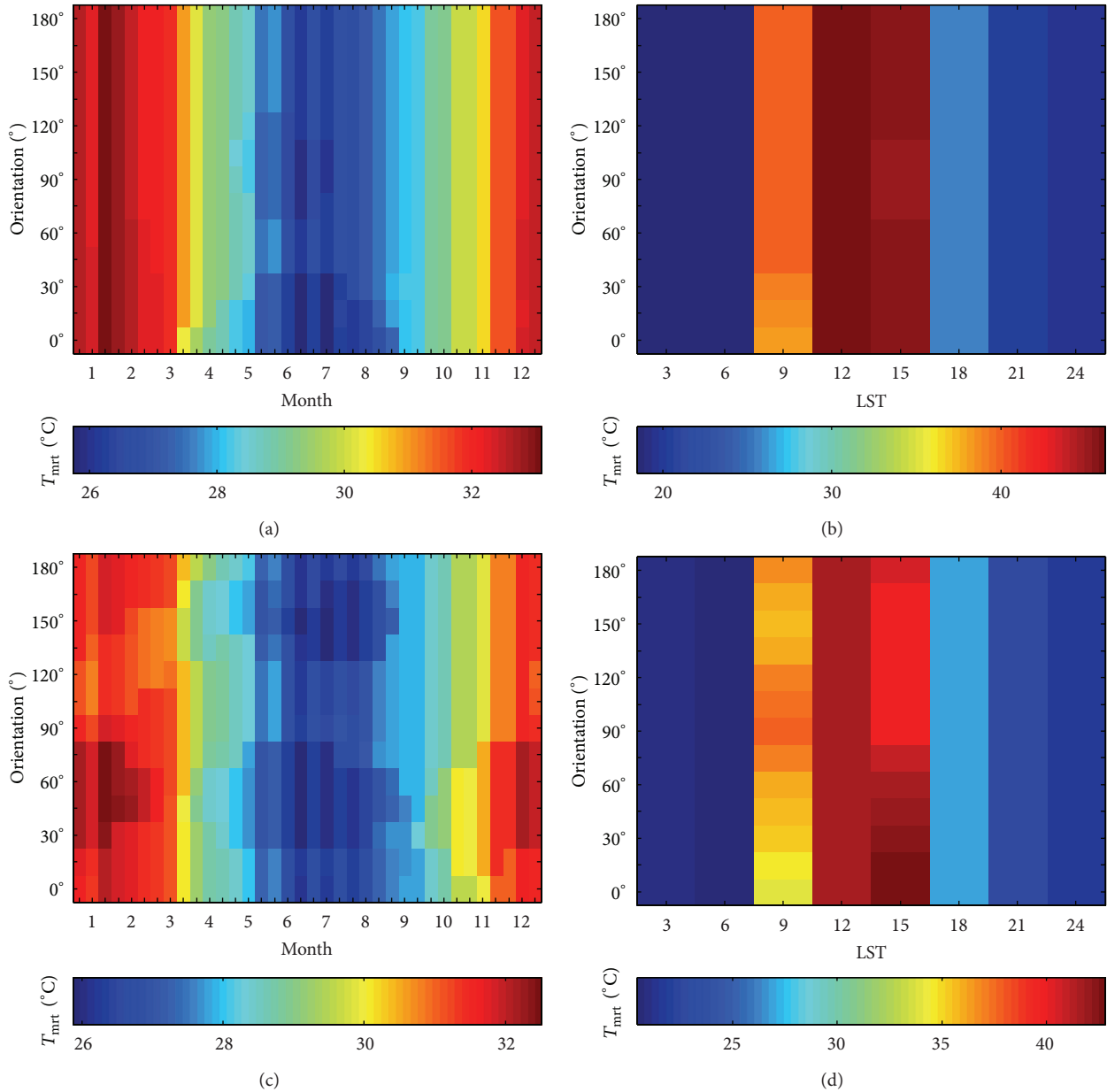


FIGURE 7: Effects of orientation on the temporal distribution of  $T_{mrt}$  at the urban street when the buildings' height was kept at 5 m, depicted in terms of the annual cycle of  $T_{mrt}$  (a) and the diurnal cycle (b). ((c) and (d)) show the corresponding effects when the buildings' height was kept at 25 m high.

the east-west direction (i.e.,  $45^\circ$  in the figure) influences the calculated thermal comfort parameters as it can be observed in Figures 7(c) and 7(d). For this case, in Dar es Salaam, the east-west oriented street could be an undesirable street orientation for pedestrian thermal comfort condition. Other studies have attributed such an orientation to be prone to solar access [3, 6]. Otherwise, the north-south oriented streets (i.e.,  $120\text{--}135^\circ$  in the figure) could present a good scenario for pedestrian thermal comfort in Dar es Salaam based on both annual and diurnal temporal distributions of  $T_{mrt}$ .

**3.3. Simulation Results in the Urban Garden.** Perhaps one of the reasons of doing simulation at the urban park is the understanding that many of the urban parks in Tanzanian cities including Dar es Salaam are relatively small in size but are also very close to surrounding buildings. The close buildings to such parks could potentially impose some significant effects on the thermal comfort in a garden or park (see MP2 in Figure 1) especially when buildings' height is too high. Figure 8, therefore, describes the effects of buildings' height on a small urban garden while the effect of orientation is illustrated in Figure 9.

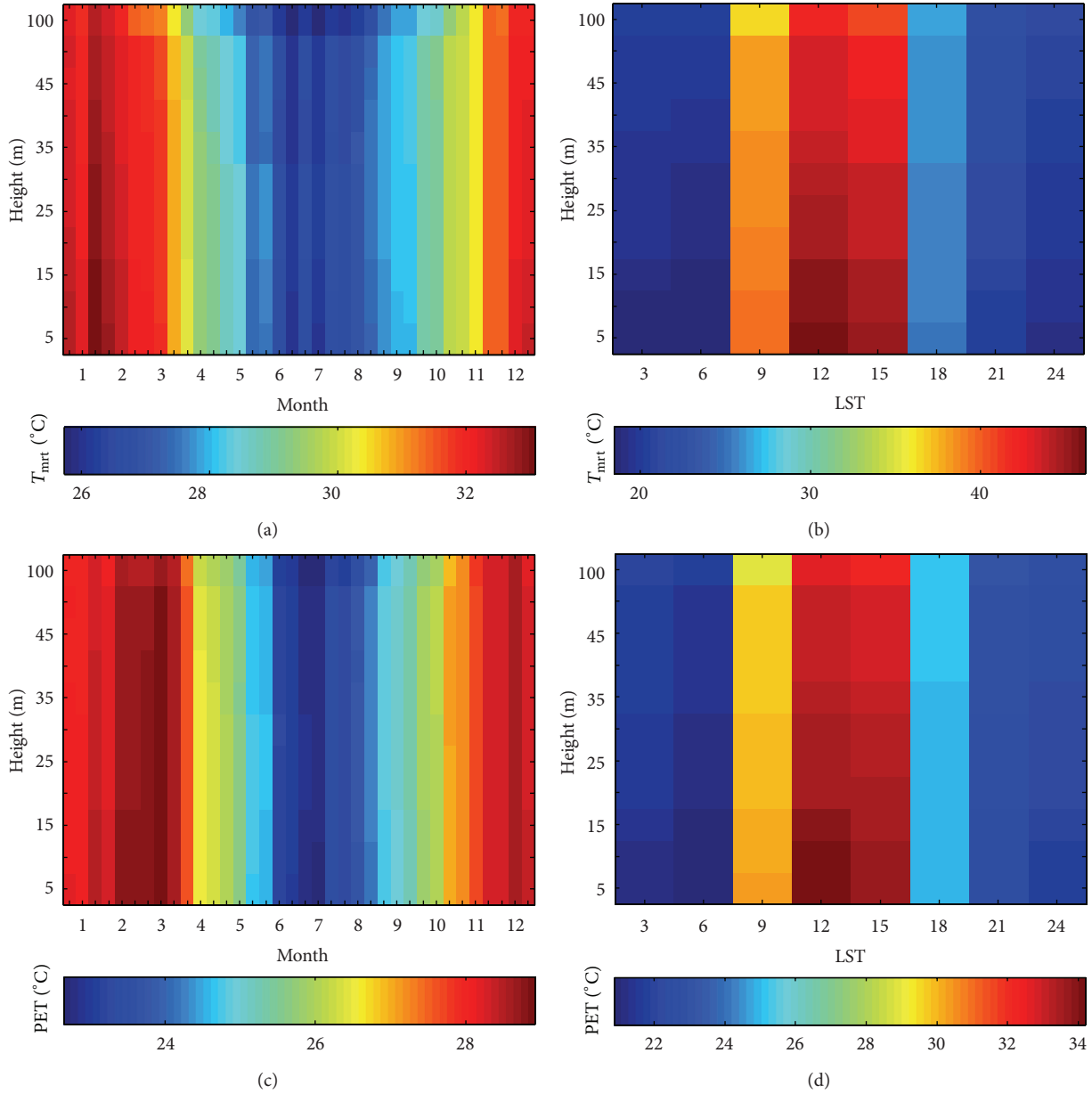


FIGURE 8: Effects of increasing buildings' height on the temporal distribution of  $T_{mrt}$  at the urban park as depicted in terms of the annual cycle (a) and diurnal cycle (b). The corresponding thermal comfort distribution is shown in terms of PET index ((c) and (d)).

The simulation results at the urban park suggested that buildings close to the park could significantly affect the thermal comfort at pedestrian level (i.e., human beings resting in an urban park), and the effects become clear as the height of the buildings increases. For instance, at a building height of 100 m, both  $T_{mrt}$  and PET values were observed to be significantly reduced (Figure 8). In order to visualize the buildings effect on the park thermal comfort, the park setup was also idealized and rotated every 15°. It should be noted that the buildings surrounding the urban parks are not usually uniformly located around the park as the case here. Results in this simulation are therefore illustrated in Figure 9.

In Figures 9(a) and 9(b), the buildings surrounding the park were kept at 5 m high, and it is clear that a significant reduction of  $T_{mrt}$  values could be reached when most of the buildings are located to the south-western side of the park (60° and 105° in the figure). In the diurnal distribution, this reduction could be revealed clearly at 9 LST. When the buildings' height was increased to 100 m, still the situation where most of them are located to the southwest side favours the significant reduction of  $T_{mrt}$  (Figures 9(a) and 9(b)). Due to the increased height of the buildings, the effect can also be observed at 15 LST on the diurnal cycle.

The simulations of varying the heights of surrounding buildings and rotating the urban park in order to determine

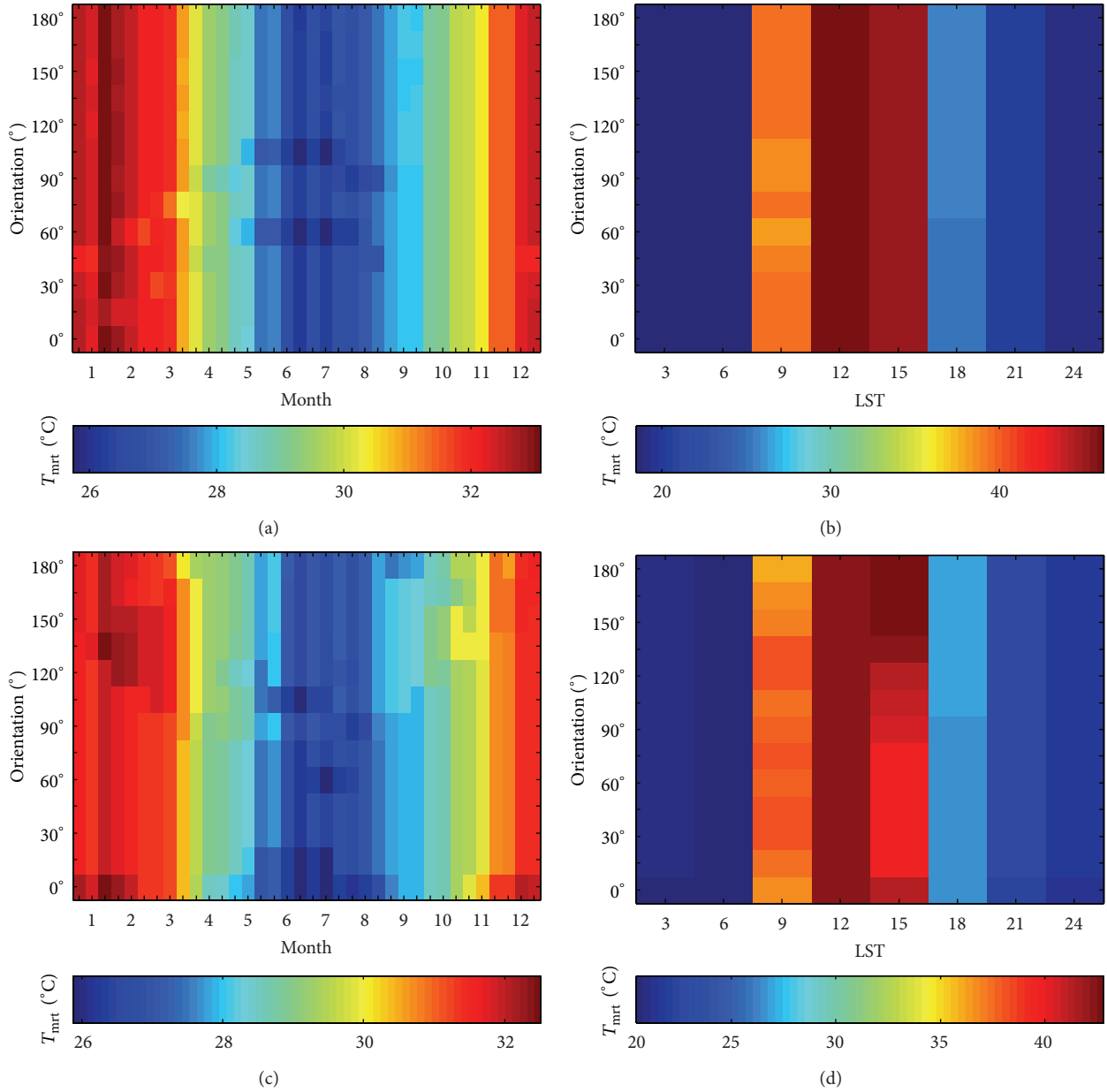


FIGURE 9: Effects of orientation on the temporal distribution of  $T_{mrt}$  at the urban park in terms of annual and diurnal cycles ((a) and (b)) with buildings' height kept at 5 m. Corresponding effect when buildings' height was increased to 100 m high ((c) and (d)).

the effect on thermal comfort at pedestrian level seems to be of a novelty in urban climate simulation studies. Many studies have concentrated on simulation of an urban canyon [3, 6, 11, 15, 38], and most of the studies suggested that at pedestrian level, the extreme cases in terms of thermal comfort parameters could be observed at the east-west and north-south orientations [3, 6, 38]. This situation was also observed in this study although with some slight differences which could be attributed to the latitudinal location of the cities which slightly affects the solar path of a particular place.

Simulation of thermal comfort for open spaces is very important especially in realizing the thermal comfort and recreation potential for the parks. Information like this has

potential impact on design implications in cities particularly in developing countries where open spaces in cities might be considerably few. It can also help in management of urban parks in the sense that optimal comfort conditions within the urban park could be attained through shading effects of plants within the park itself and the influence of nearby buildings. In this study, buildings' height was particularly observed to exert a decisive role in altering the thermal comfort parameter values. Although, generally the increase in buildings' height was observed to favour reduction in thermal comfort parameters mainly through altering the solar access, this could also have an effect on the wind flow as already discussed in [15]. For Dar es Salaam example, any design

affecting the city open spaces should consider taking the advantage of the sea breezes too.

#### 4. Conclusion

Due to its economic importance in eastern and central Africa, Dar es Salaam city is growing fast. There are increasingly many tall buildings especially in the central business district. Although there are no continuous measurements of urban climate, simulation of urban climate especially to quantify the effects of building and street orientation at pedestrian level using the easily available synoptic data is important and could provide applicable information in terms of urban planning in developing countries. Simulation of urban climate at pedestrian level is also of crucial impact in tropical cities since most of the activities are outdoors. For instance, in Dar es Salaam, there are lot of street vendors who spend most of their daytime hours outside in streets. Thus, the results provided in this study could help in redesigning the streets that ensure thermal comfort at pedestrian level through the variation of buildings' height and orientation.

The simulations performed in this study shows that the thermal comfort parameters ( $T_{mrt}$  and PET) at both the urban street and the park can be significantly affected by the urban configuration. Optimal reduction of  $T_{mrt}$  and PET values could particularly be obtained on the north-south reoriented streets and with increased buildings' heights. Additionally, the results from the simulations undertaken on a small urban park provided a novelty in design implications and management of open spaces in many cities in the developing countries including Dar es Salaam. These should also help planners understand the potential of open spaces on improving the microclimates in urban areas. The results of this study could also ultimately assist planners in determining appropriate configuration in urban growth areas of Tanzania and elsewhere. Further urban spatial modelling of open spaces in Dar es Salaam is also suggested involving more microscale models for the sake of having robust and firm bioclimatic information to assist in urban planning and management of open spaces.

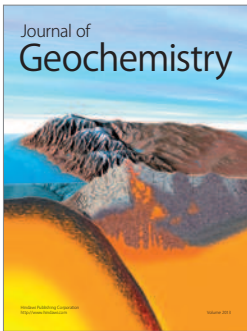
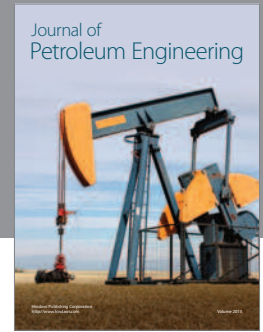
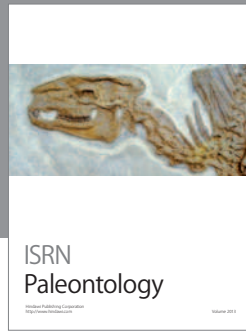
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#### References

- [1] S. Nieuwolt, "Breezes along the Tanzanian East Coast," *Archiv für Meteorologie Geophysik und Bioklimatologie B*, vol. 21, no. 2-3, pp. 189–206, 1973.
- [2] E. L. Ndetto and A. Matzarakis, "Basic analysis of climate and urban bioclimate of Dar es Salaam, Tanzania," *Theoretical and Applied Climatology*, 2013.
- [3] F. Ali-Toudert and H. Mayer, "Thermal comfort in an east-west oriented street canyon in Freiburg (Germany) under hot summer conditions," *Theoretical and Applied Climatology*, vol. 87, no. 1–4, pp. 223–237, 2007.
- [4] I. Charalampopoulos, I. Tsiros, A. Chronopoulou-Sereli, and A. Matzarakis, "Analysis of thermal bioclimate in various urban configurations in Athens, Greece," *Urban Ecosystems*, vol. 16, no. 2, pp. 217–233, 2013.
- [5] F. Bourbia and F. Boucheriba, "Impact of street design on urban microclimate for semi arid climate (Constantine)," *Renewable Energy*, vol. 35, no. 2, pp. 343–347, 2010.
- [6] F. Ali-Toudert and H. Mayer, "Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate," *Building and Environment*, vol. 41, no. 2, pp. 94–108, 2006.
- [7] T.-P. Lin, A. Matzarakis, and R.-L. Hwang, "Shading effect on long-term outdoor thermal comfort," *Building and Environment*, vol. 45, no. 1, pp. 213–221, 2010.
- [8] E. Johansson, "Influence of urban geometry on outdoor thermal comfort in a hot dry climate: a study in Fez, Morocco," *Building and Environment*, vol. 41, no. 10, pp. 1326–1338, 2006.
- [9] H. Sugawara, A. Hagishima, K. Narita, H. Ogawa, and M. Yamano, "Temperature and wind distribution in an EW-oriented urban street canyon," *Scientific Online Letters of the Atmosphere (SOLA)*, vol. 4, pp. 53–56, 2008.
- [10] R. Emmanuel and E. Johansson, "Influence of urban morphology and sea breeze on hot humid microclimate: the case of Colombo, Sri Lanka," *Climate Research*, vol. 30, no. 3, pp. 189–200, 2006.
- [11] E. Johansson and R. Emmanuel, "The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka," *International Journal of Biometeorology*, vol. 51, no. 2, pp. 119–133, 2006.
- [12] A. Lopes, S. Lopes, A. Matzarakis, and M. J. Alcoforado, "The influence of the summer sea breeze on thermal comfort in funchal (Madeira). A contribution to tourism and urban planning," *Meteorologische Zeitschrift*, vol. 20, no. 5, pp. 553–564, 2011.
- [13] S. Ahmad, N. M. Hashim, Y. M. Jani, and N. Ali, "The impacts of sea breeze on urban thermal environment in tropical coastal area," *Advances in Natural and Applied Sciences*, vol. 6, no. 1, pp. 71–78, 2012.
- [14] E. L. Krüger and F. A. Rossi, "Effect of personal and microclimatic variables on observed thermal sensation from a field study in southern Brazil," *Building and Environment*, vol. 46, no. 3, pp. 690–697, 2011.
- [15] R. Emmanuel, H. Rosenlund, and E. Johansson, "Urban shading—a design option for the tropics? A study in Colombo, Sri Lanka," *International Journal of Climatology*, vol. 27, no. 14, pp. 1995–2004, 2007.
- [16] A. Matzarakis, F. Rutz, and H. Mayer, "Modelling radiation fluxes in simple and complex environments—application of the RayMan model," *International Journal of Biometeorology*, vol. 51, no. 4, pp. 323–334, 2007.
- [17] A. Matzarakis, F. Rutz, and H. Mayer, "Modelling radiation fluxes in simple and complex environments: basics of the RayMan model," *International Journal of Biometeorology*, vol. 54, no. 2, pp. 131–139, 2010.
- [18] S. Thorsson, F. Lindberg, I. Eliasson, and B. Holmer, "Different methods for estimating the mean radiant temperature in an outdoor urban setting," *International Journal of Climatology*, vol. 27, no. 14, pp. 1983–1993, 2007.

- [19] P. Jonsson, C. Bennet, I. Eliasson, and E. Selin Lindgren, "Suspended particulate matter and its relations to the urban climate in Dar es Salaam, Tanzania," *Atmospheric Environment*, vol. 38, no. 25, pp. 4175–4181, 2004.
- [20] S. E. Mbuligwe and G. R. Kassenga, "Automobile air pollution in Dar es Salaam City, Tanzania," *Science of the Total Environment*, vol. 199, no. 3, pp. 227–235, 1997.
- [21] A. Hill and C. Lindner, *Modelling Informal Urban Growth Under Rapid Urbanisation: A CA-Based Land-Use Simulation Model for the City of Dar Es Salaam, Tanzania*, Technische Universität Dortmund, Dortmund, Germany, 2010.
- [22] F. R. Fosberg, B. J. Garnier, and A. W. Kuchler, "Delimitation of the humid tropics," *Geographical Review*, vol. 51, no. 3, pp. 333–347, 1961.
- [23] M. Roth, "Review of urban climate research in (sub)tropical regions," *International Journal of Climatology*, vol. 27, no. 14, pp. 1859–1873, 2007.
- [24] C. Howorth, I. Convery, and P. O'Keefe, "Gardening to reduce hazard: urban agriculture in Tanzania," *Land Degradation and Development*, vol. 12, no. 3, pp. 285–291, 2001.
- [25] W. Kuttler, "Stadtklimain," in *Handbuch der Umweltveränderungen und Ökotoxologie*, R. Guderian, Ed., pp. 420–470, Springer, Berlin, Germany.
- [26] A. Matzarakis, M. Rocco, and G. Najjar, "Thermal bioclimate in Strasbourg—the 2003 heat wave," *Theoretical and Applied Climatology*, vol. 98, no. 3–4, pp. 209–220, 2009.
- [27] M. G. Kendall, "A new measure of rank correlation," *Biometrika*, vol. 30, no. 1/2, pp. 81–93, 1938.
- [28] A. Matzarakis, H. Mayer, and M. G. Iziomon, "Applications of a universal thermal index: physiological equivalent temperature," *International Journal of Biometeorology*, vol. 43, no. 2, pp. 76–84, 1999.
- [29] H. Mayer and P. Höppe, "Thermal comfort of man in different urban environments," *Theoretical and Applied Climatology*, vol. 38, no. 1, pp. 43–49, 1987.
- [30] P. Höppe, "The physiological equivalent temperature—a universal index for the biometeorological assessment of the thermal environment," *International Journal of Biometeorology*, vol. 43, no. 2, pp. 71–75, 1999.
- [31] D. J. Wessel, *Ashrae Fundamentals Handbook 2001*, ASHRAE, Atlanta, Ga, USA, 2001.
- [32] A. Matzarakis, F. Rutz, and H. Mayer, "Modelling radiation fluxes in simple and complex environments—application of the RayMan model," *International Journal of Biometeorology*, vol. 51, no. 4, pp. 323–334, 2007.
- [33] G. L. Makokha and C. A. Shisanya, "Trends in mean annual minimum and maximum near surface temperature in Nairobi City, Kenya," *Advances in Meteorology*, vol. 2010, Article ID 676041, 6 pages, 2010.
- [34] O. Akinbode, A. Eludoyin, and O. Fashae, "Temperature and relative humidity distributions in a medium-size administrative town in southwest Nigeria," *Journal of Environmental Management*, vol. 87, no. 1, pp. 95–105, 2008.
- [35] R. Emmanuel, "Thermal comfort implications of urbanization in a warm-humid city: the Colombo Metropolitan Region (CMR), Sri Lanka," *Building and Environment*, vol. 40, no. 12, pp. 1591–1601, 2005.
- [36] C. Grimmond, S. Potter, H. Zutter, and C. Souch, "Rapid methods to estimate sky-view factors applied to urban areas," *International Journal of Climatology*, vol. 21, no. 7, pp. 903–913, 2001.
- [37] N. D. Burgess and G. P. Clarke, *Coastal Forests of Eastern Africa*, IUCN, Gland, Switzerland, 2000.
- [38] J. Herrmann and A. Matzarakis, "Mean radiant temperature in idealised urban canyons—examples from Freiburg, Germany," *International Journal of Biometeorology*, vol. 56, no. 1, pp. 199–203, 2012.



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