The role of urban design in enhancing the microclimate and thermal comfort in warm-humid Dar es Salaam, Tanzania

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Dated: 15th June 2015

Abstract

Due to the complexity of the outdoor environment, urban design patterns considerably affect the microclimate and outdoor thermal comfort in a given urban morphology. Parameters such as building height and orientation, spaces between buildings, plot coverage, etc influence the microclimate in terms of solar access, shade, wind speed and direction. In warm-humid Dar es Salaam, the consideration of microclimate and outdoor thermal comfort in urban design has received little attention although the urban planning authorities try to develop the quality of planning and design. The main aim of this study is to investigate the relationship between urban design, urban microclimate and outdoor comfort in four different areas in the city of Dar es Salaam, during the wet and dry seasons. This investigation is mainly based on microclimate simulations using ENVI-met and different existing urban morphologies are climatically and thermally studied including low, medium and high rise buildings. Parameters such as Mean Radiant Temperature (MRT), wind speed and Physiological Equivalent Temperature index (PET) are presented as thermal maps to highlight the strengths and weaknesses of the existing urban design in the city. The study illustrates that the areas with low-rise buildings lead to higher MRT values than the areas with high-rise buildings. The results also show that the use of dense trees helps to enhance the thermal conditions, but it might negatively affect the wind ventilation in the outdoor spaces. This study provides a set of guidelines on how to develop the existing situation from microclimate and thermal comfort perspectives. Such guidelines will help architects and urban designers to increase the quality of outdoor environment and demonstrate the need to create better urban spaces in harmony with microclimate and thermal comfort.

1. Introduction

In developing countries, increasing urbanization has become a problem that affects the urban environment and lead to a poor urban health. Such rapid urbanization generated a mixture of regular and irregular housing areas with different urban design patterns. This complexity of different urban forms and building densities affects the microclimate and thermal comfort in the related area. In warm-humid climates, the consideration of providing shade and ventilation in outdoor urban spaces is crucial in urban design and planning. Jusuf et al. (2007) argued that the appropriate land use and planning in Singapore could mitigate the Urban Heat Island (UHI). Aynsley and Gulson (1999) highlighted the impotence of planning tools, standards and guidelines to achieve shading and breeze penetration solutions in the humid tropics. In addition, studies such as Yahia and Johansson (2013) demonstrated that the urban planning regulations have an impact on microclimate in urban streets, attached and detached urban forms. Therefore a considerable development based on the climate requirements has to be taken into account (Yahia and Johansson, 2013). Ng (2009) proposed a set of guidelines and recommendations to be considered in urban planning policies of the high-density of Hong Kong. The author recommended maximizing the air ventilation in urban areas by considering a variation in building heights, street orientation towards the prevailing wind, planting tall trees with wide and dense canopies along streets for maximizing the pedestrian comfort and reducing the UHI effect (Ng, 2009).

In the warm- humid city of Dar es Salaam which is considered as one of the fastest growing cities in the world, Ndetto and Matzarakis (2015) argued that the poor planning has led to many inhabitants to settle themselves in low-rise zones, whereas much of the central business districts consist of compact mid-rise and high-rise geometries. This increase of the built-up areas influenced the urban climate. Different human thermal indices documented that the afternoon is the warmest period in Dar es Salaam (Ndetto and Matzarakis, 2015).

In 2012, the Ministry of Lands, Housing and Human Settlements Development issued a new master plan in addition to urban planning act documents in Dar es Salaam for the period 2012-2032. These regulations govern the planning aspects such as zoning, land use planning, space standards, etc. Moreover, different urban forms were applied such as high-rise and low-rise buildings with different building densities. However, the consideration of microclimate and outdoor thermal comfort in urban design and planning regulations has received little attention although the urban planning authorities try to develop the quality of planning and design. Therefore, the aim of this paper is to investigate the relationship between urban design, urban microclimate and outdoor comfort in four different areas in the city of Dar es Salaam, during the wet and dry seasons.

2. Methodology

2.1 The city of Dar es Salaam and the studied areas

Dar es Salaam is located at the south west of the Indian Ocean coast with land area about 1000 km^2 (Jonsson et al, 2004).The climate is typically warm-humid, and affected by the monsoon (between March and October, the monsoon blows from the northeast whereas between October and March, the city is affected by the southeast monsoon). Generally, the relative humidity in Dar es Salaam ranges between 67 and 96% in a year, and the mean annual air temperature is about 30°C with slight seasonal changes because of the proximity to the equator. The period from May to September is the coolest whereas the hottest period is between December and March (Ndetto and Matzarakis, 2015). Therefore the months February and July – as representative months for summer and winter respectively – were selected to be studied in this paper. The population in Dar es Salaam is increasing by time and has exceeded 4,364,541 inhabitants in 2012 with a growth rate of 5.6% (The United Republic of Tanzania 2013). At the same time, the built-up area reached 30.8 km^2 (Lupala 2002). The development in the industry and commerce has been considered mainly in areas located in the inner city such as the City Center and Kariakoo where high-rise buildings have been constructed. On the other hand and due to the rapid urbanization, urban sprawl has been the main problem that affects the urbanization in Dar es Salaam (Lupala 2002). This can be easily noticed in the many low-density areas with low-rise buildings. The area Manzese is an example. In addition, areas with two and three stories (as single house or villa) can also be found such as the area Upanga. In this paper, four areas with different urban forms (the City Center, Kariakoo, Manzese and Upanga) were studied to investigate the impact of urban design on microclimate in Dar es Salaam (See Fig. 1).

2.2 Microclimate simulation (modeling structure, procedures and calibration)

Microclimate simulations were carried out by using ENVI-met 3.1 (Bruse, 2013). The program uses a three-dimensional computational fluid dynamics and energy balance model. This study focuses on the hot period in Dar es Salaam, i.e. mainly one day (28st February) was simulated. However, a complementary simulation of the area Upanga was carried out for the cool period represented by 15th July. For all investigations, the simulated period lasted from 5:00 Local Time (LT) in the morning until 16:00 in the afternoon in order to include the maximum air temperature, which normally occurs at 14:00. Thus, the peak hour 14:00 was mainly studied. Both urban streets and spaces between buildings were investigated. In addition, the relationship between the outdoor thermal comfort and Sky View Factor (SVF) is also examined in the four studied areas. The four simulated areas have the same model size 160 m x 160 m (the model grid resolution was 1 m in directions dx and dy). However, the areas varied in the vertical dimension (the building heights varied from 3 to 55 m) due to the differences in land-use, building functions and/or planning regulations. Therefore, the model grid resolution for the dz was set as 4 m. The simulated areas are shown in Fig. 1.

(a) (b) (c) (d)

Fig. 1 Physical characteristics of the studied areas, where (a) Kariakoo, (b) City Center, (c) Manzese and (d) Upanga

In order to achieve realistic results, the simulations were compared with on site annual ongoing measurements. The site was modelled as accurately as possible as regards geometries, street orientation, etc by using metadata from a satellite image for Dar es Salaam (as raster data). In addition, the building heights were measured on site by using a Nikon® Laser 550 Rangefinder.

Several studies have pointed out that ENVI-met underestimates the diurnal temperature fluctuations (Ali-Toudert & Mayer, 2006; Yahia and Johansson, 2014). This is because ENVI-met does the urban climate calculations at a micro or local scale and that larger regional (meso scale) effects are not taken into account (Bruse, 2013). Since we are mainly focussing on the specific hour that is the warmest, the input values for the calibration process were set to reach the measured values at 14:00 and thus the initial temperature was overestimated at the start of the simulations (hour 5:00).

2.3 Assignment of microclimate and thermal comfort outdoors

In order to assess microclimate and outdoor thermal comfort in different outdoor built up environments, the

Mean Radiant Temperature (MRT) and the Physiological Equivalent Temperature (PET) index (Mayer and Höppe, 1987) were calculated as indicators. The reason to choose PET is that it is widely used in different climate studies including the warm humid Dar es Salaam (Ndetto and Matzarakis, 2015). Additionally, PET is expressed in °C which makes it easier to understand by architects and planners. It is based on the energy balance of the human body. Although the PET index has not been calibrated for Dar es Salaam, it is possible to use it to compare different urban morphologies in the city. In this study, the RayMan PC model (Matzarakis et al, 2007) is used to calculate PET.

2.4 The role of vegetation

This study highlights the importance of vegetation in urban design to provide shade. However, the main focus is to study the relationship between the vegetation (as an urban design element) and SVF in the areas especially in Upanga which has plenty of vegetation. To do this, two different simulations are conducted in the month of February; the first is the existing situation including vegetation whereas the second simulation is conducted without vegetation. The simulated trees in ENVI-met are designed according to a real observation and therefore two different Leaf Area Index (LAI) (Meir, Grace, & Miranda, 2000) – are applied. Dense trees with 10 m height (LAI = 4.73) and very dense trees (15 m height) with LAI = 14 are designed for simulating the trees. In addition, grass (10 cm height) with LAI = 0.03 is also used. The LAI is calculated according to previous studies (Yahia and Johansson, 2014).

3. Results and Discussion

3.1 Microclimate spatial variations

Fig. 2 shows the spatial variation of MRT in the four studied areas in February. The result illustrates that the streets receive high amount of radiation (MRT reaches up to around 60°C in all areas). In Kariakoo and City Center, MRT values at the spaces between buildings tend to be lower than at the streets. This is perhaps due to the compact urban morphologies with high buildings that provide shading and prevent solar radiation to reach the ground and therefore the MRT is lower (MRT is about 34 and 50 °C). On the other hand, due to the low building heights in Manzese and Upanga, the spaces between buildings receive more radiation compared to Kariakoo and City Center. These results agree well with other studies in Tanzania such as Ndetto and Matzarakis (2013) which argued that a significant reduction of MRT and PET values can be observed at the buildings' height of 20 m and more reduction at the height of 100m. However, Upanga has detached buildings and plenty of vegetation. This combination positively affects the MRT values at the spaces between buildings and thus the MRT values tend to be lower than in Manzese although Manzese has more compact morphologies and have similar building heights (3-6 m).

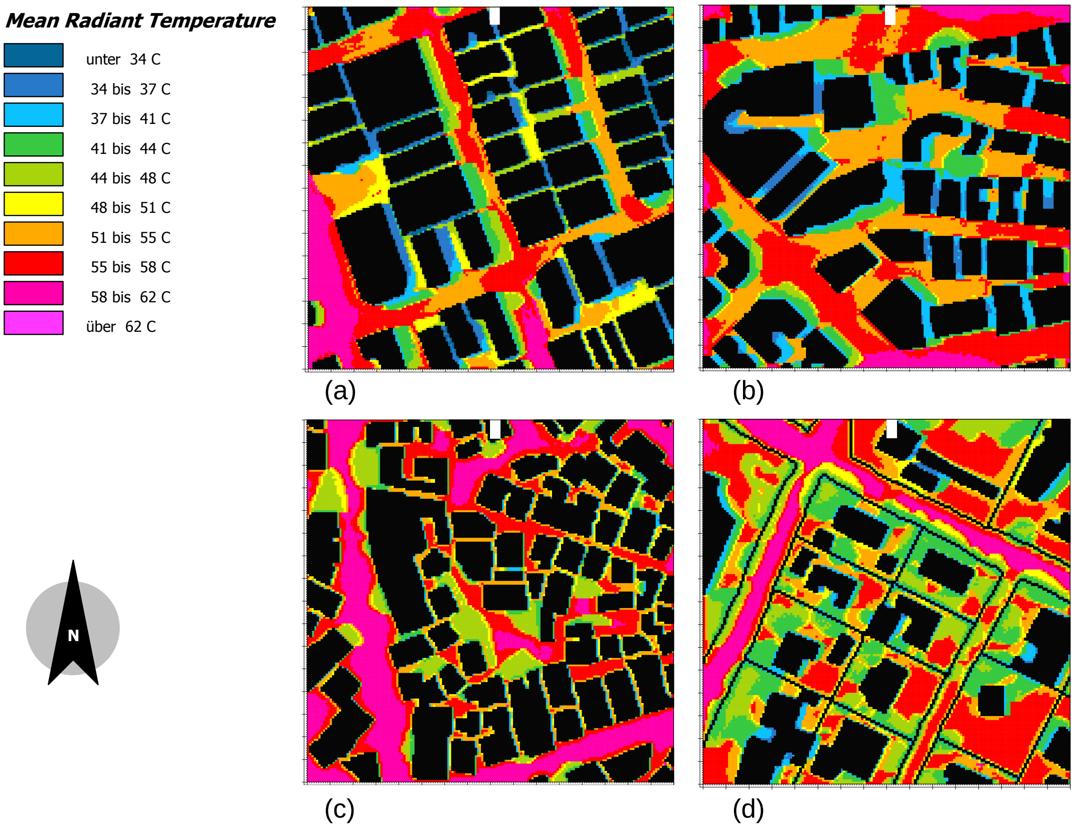


Fig. 2 MRT spatial distribution at 14:00 LT in the four studied area in February, where (a) Kariakoo, (b) City Center, (c) Manzese and (d) Upanga

Fig. 3 shows the wind speed distribution at 14:00 LT in the four studied areas in February. The results reveal that the lowest wind speed is about 0.2 m/s at the pedestrian level whereas the highest is about 2.2 m/s. In general, it is noted that the central areas in addition to the spaces between buildings have less wind speed than the surrounding spaces. Moreover, the streets which are perpendicular to the prevailing wind direction (45 degrees) are less ventilated than the streets which have the same direction as the wind. The results illustrate that the areas Menzese and Upanga are slightly more ventilated than Kariakoo and City Center due to the low building heights as well as the street orientation towards the prevailing wind, whereas the situation in the City Center is better than in Kariakoo because the spaces between buildings in the City Center are wider and allow the wind to better penetrate the area. The results agree will Ng (2009) who argued that it is important for better urban air ventilation in a dense, hot–humid city to let more wind penetrate through the urban district. Breezeways can be in the form of roads, open spaces and low-rise building corridors. It is also recommended that the array of main streets, or breezeways should be aligned in parallel, or up to 30 to the prevailing wind direction, in order to maximize the penetration of prevailing wind through the area (Ng, 2009).

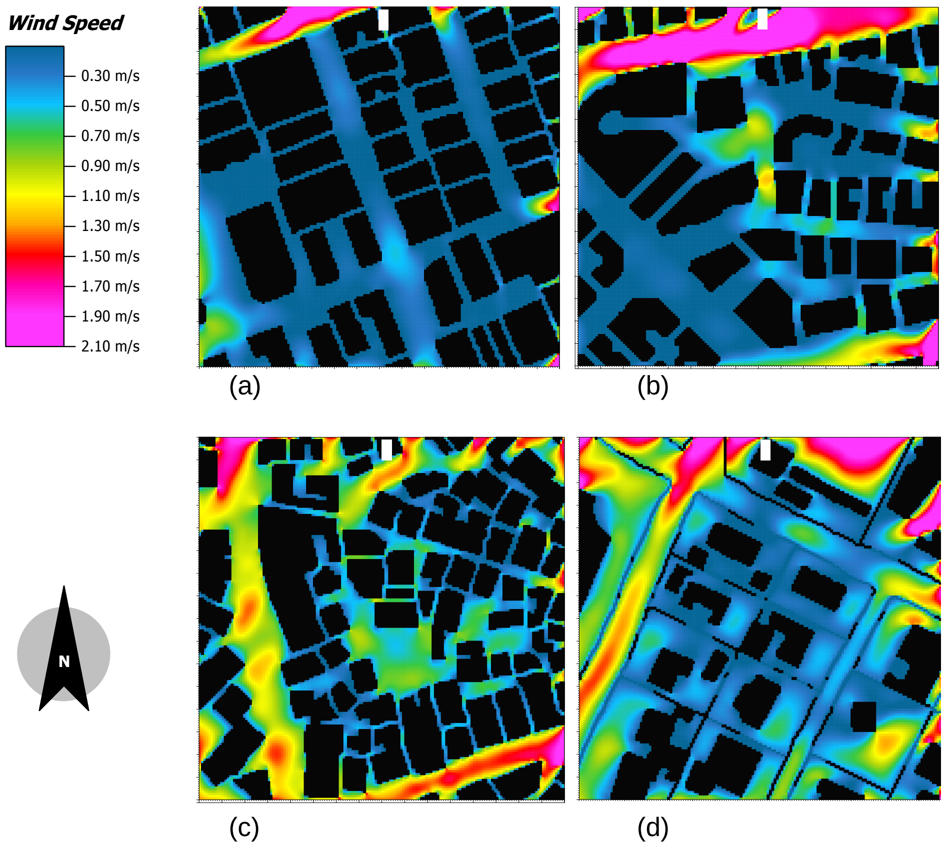
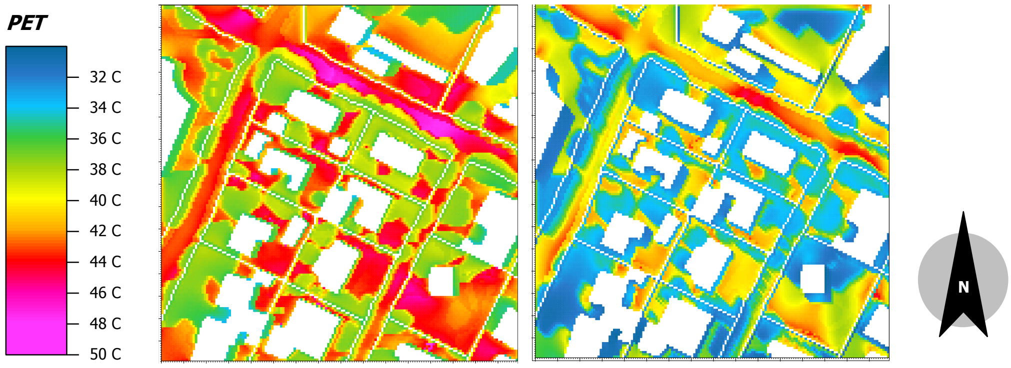


Fig. 3 Wind speed distribution at 14:00 LT in the four studied area in February, where (a) Kariakoo, (b) City Center, (c) Manzese and (d) Upanga

3.2 Thermal comfort seasonal differences

Fig. 4 illustrates the spatial variation of PET in Upanga during (a) February and (b) July. It is very clear that there is a significant difference in the thermal comfort situation, i.e. Upanga is more comfortable in July than in February. In February, the average value for PET in the urban spaces is about 41 °C; the minimum PET value is about 35 °C in some spots (mainly under the trees) whereas the highest value is about 48 °C mainly at the middle of the street which is perpendicular to the wind direction. In July, the average value for PET in the urban spaces is about 37 °C; the minimum PET value is about 32 °C in many spots under the trees, whereas the highest value is about 43 °C mainly at the middle of the street which is perpendicular to the wind direction. These values are higher than in the previous studies in Tanzania such as Ndetto and Matzarakis (2013) who recorded a high PET value of 34°C between 12:00 and 15:00 LT in the months of February, March, November, and December. This discrepancy can be due to possible differences in urban forms, area building densities, street patterns, vegetation types, etc.

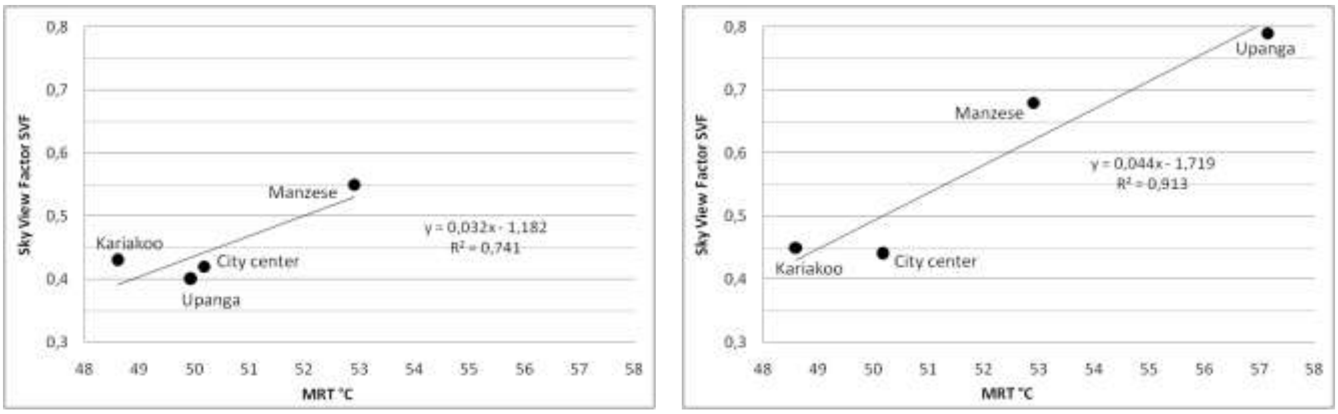


(a) (b)

Fig. 4 PET distribution at 14:00 LT in Upanga during (a) February and (b) July

3.3 The effect of SVF and vegetation on MRT

Fig. 5 shows the correlation between SVF and MRT in the urban spaces of the four areas in February, where (a) is the existing situation including buildings and vegetation, whereas (b) is the situation in Upanga where the vegetation is taken out and therefore SVF is mainly calculated as a result of the buildings. Since the difference between SVF (buildings and vegetation) and SVF (only buildings) in Kariakoo, City Centre and Manzese is only about 0.1, the difference in MRT (the average value in the urban spaces) was neglected and therefore, the same MRT average values were applied in the investigation. In Upanga, the difference of SVF is significant (about 0.35) and therefore, the new simulation was conducted in order to calculate the average MRT value in the urban spaces. In both cases, the results reveal that the higher SVF value, the higher MRT value. Fig. 5a shows that Manzese has the highest SVF value (0.55) and this corresponds to the highest MRT average value (53 °C). The area Upanga in Fig. 5a has the lowest SVF (0.4). However, due to the vegetation cover, the MRT is very low but not as low as in Kariakoo. This can be perhaps be due to the leaf densities that allowed some amount of solar radiation to penetrate and reach the ground, whereas in Kariakoo which has the lowest MRT average value (48.5 °C), the shade caused by buildings was the main reason to have such MRT average value. The effect of SVF on MRT is significantly clearer in Fig. 5b where only buildings are considered. Fig. 5b illustrates that Upanga has the highest SVF value (about 0.8) and this corresponds to the highest MRT value (57 °C). The results reveal that the relationship between SVF and MRT is strongly significant when detached buildings are investigated without vegetation (R^2= 0.9), whereas this relationship is less significant when the vegetation is taken into account. Other studies such as Krüger et al. (2011) argued that the MRT, which is strongly affected by solar radiation, is more related to the SVF than air temperature. However, the authors recommended that the SVF, when analyzed as an isolated parameter, is not able to accurately predict the thermal conditions of a given area. Thus, a combined analysis of the SVF and the solar charts can provide more accurate results than the SVF alone (Krüger et al., 2011)



(a) (b)

Fig. 5 Relationship between SVF and MRT for the four studied areas in February at 14:00 LT where (a) SVF is considered as buildings plus vegetation and (b) SVF is only a result of buildings

4. Conclusions

The study investigated the relationship between urban design, urban microclimate and outdoor comfort in four different areas in the city of Dar es Salaam, during the wet and dry seasons. It was noted that the MRT values at the spaces between buildings tend to be lower than at the streets due to the compact urban morphologies with high buildings that provide shading. Therefore, it is highly recommended to consider the microclimate street design as a part of urban planning regulation in the city. The study showed the positive effect of shade from both buildings and trees. Thus, it is strongly recommended to combine different solutions to provide shade. This study illustrated that the areas Manzese and Upanga are slightly more ventilated than Kariakoo and City Center due to the low building heights as well as the street orientation towards the prevailing wind, whereas the situation in the City Center is better than in Kariakoo since the spaces between buildings in the City Center are wider and allow the wind to better penetrate the area. Therefore, orienting the streets towards the prevailing wind direction (with wide corridors) has definitely a positive effect to ventilating the urban areas. Regarding the thermal comfort, the month July is more comfortable than February (a difference of 4 °C PET was recorded as an average value in the urban spaces of Upanga). The results also argued that the relationship between SVF and MRT is strongly significant when detached buildings are investigated without vegetation, whereas this relationship is less significant when the vegetation is taken into account.

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