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ORIGINAL PAPER

Basic analysis of climate and urban bioclimate of Dar es Salaam, Tanzania

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Abstract Better understanding of urban microclimate and bioclimate of any city is imperative today when the world is constrained by both urbanisation and global climate change. Urbanisation generally triggers changes in land cover and hence influencing the urban local climate. Dar es Salaam city in Tanzania is one of the fast growing cities. Assessment of its urban climate and the human biometeorological conditions was done using the easily available synoptic meteorological data covering the period 2001–2011. In particular, the physiologically equivalent temperature (PET) was calculated using the RayMan software and results reveal that the afternoon period from December to February (DJF season) is relatively the most thermal stressful period to human beings in Dar es Salaam where PET values of above 35 °C were found. Additionally, the diurnal cycle of the individual meteorological elements that influence the PET index were analysed and found that air temperature of 30–35 °C dominate the afternoon period from 12:00 to 15:00 hours local standard time at about 60 % of occurrence. The current results, though considered as preliminary to the ongoing urban climate study in the city, provide an insight on how urban climate research is of significant importance in providing useful climatic information for ensuring quality of life and wellbeing of city dwellers.

1 Introduction

Dar es Salaam is one of the current fastest growing cities in the world with an average annual growth for 2006 to 2020 at 4.4 %, ranking ninth in the world. At present, its population is estimated at three million inhabitants being the second most populated city in East Africa after Nairobi. But it is projected to have 5.1 million in 2020 hence becoming the most populous city in East Africa surpassing Nairobi (citymayors statistics 2011). Dar es Salaam comprises about one third of the urban population of Tanzania (Abebe 2011). Though, urbanisation can be mostly driven by economic growth, it calls for multidisciplinary action particularly research in order to ensure improvement on quality of life and minimization of environmental problems. Like other cities in developing countries in Africa, Dar es Salaam is vulnerable to many environmental problems including flash flooding, air pollution and urban bioclimate (Douglas et al. 2008). Climate change also may jeopardise the urban life in Dar es Salaam due to its projected impacts of coastal erosion, sea level rise and the possibility of thermal discomfort as the air temperature continue to rise. Multidisciplinary research makes available important information for town planers and policy makers for better management of towns and wellbeing of inhabitants (Chen and Ng 2011). It is therefore the goal of this study to examine the changes occurring on the land surface due to urbanisation of the Dar es Salaam city and how these changes affect the microclimate of the city in conjunction with the play of the ocean. The present paper then reports the first results about the current urban bioclimate while setting the avenue for the future work.

Usually, cities will grow at the expense of continued land cover changes and the natural environment particularly vegetation. Due to land use and land cover changes in cities attributed by urbanisation, tremendous changes occur in form of landscape. This produces changes in that particular area's air (Chen and Ng 2011). One particular characteristic feature of growing cities in developing countries is urban sprawl, a problem also revealed in Pauchard et al. (2006) who called for more research on the impacts of urban sprawl

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on biodiversity in the developing world. Urban sprawl is mainly been caused by population and income growth and environmental negligence in connection to relaxed legal regulations. Urban sprawl is reported to alter a large land surface area hence consequently the atmosphere surface energy budget is being affected. The later is what brings changes in urban microclimate. As urban microclimate change, human bioclimatic conditions could also significantly be altered depending on the extent of land cover changes (Barradas 1991). An early urban climate study done using remote sensing information for 1,000 km^2 region of Centre County, Pennsylvania, USA revealed that changes in the surface microclimate is significantly related to fractional decrease in vegetation cover (Owen et al. 1998). And while studying the warm–humid city of Colombo, Sri Lanka, Emmanuel (2005) called for simulation studies to be done in order to prove the links between "hard" land cover changes and bioclimatic changes in tropical regions.

It has already been established that buildings' height does not significantly contribute to the regional climate, while it is the size of urban areas that plays an important role in the spatial extent of air temperature and precipitation disturbances (Trusilova 2006). Though, most dramatic changes can be seen in terms of air temperature, effects of the expanded urban land cover on precipitation might also be amplified with the further urban expansion and hence cannot be ignored in the future climate projections on local and regional scales.

Apart from the nature and type of land cover changes, urban microclimate of a particular city can be greatly modified by the presence of topographic features like mountain, forests and water bodies. Also urban microclimate is influenced by the geographic location and season of the year. For instance, temperate cities will display a different urban heat island to that experienced in tropical cities but also it is different to that experienced in summer or winter times (Arnfield 2003; Roth 2007). Due to changing seasons attributed to climate change, it is also anticipated that urban microclimate can be greatly affected and this call for continued urban climatology studies especially to cities in developing countries where adaptation capacity is nevertheless the least. Additionally, Dar es Salaam lies along the Western Indian Ocean coast and influence of sea in form of sea surface temperature and sea/land breezes on urban microclimate and bioclimate could be high at times of the year. The understanding of such relationship is also of utmost importance especially in urban planning particularly to cities in the hot–humid climates (Emmanuel and Johansson 2006; Lopes et al. 2011; Nieuwolt 1973).

While there have been many studies about urban climatology in Europe and North America, few studies are being done in the tropics (Jauregui 2005; Jansson 2006). In East Africa for instance, recent studies done in Nairobi reveal that urban modification of minimum air temperature is high suggesting a high warming and low cooling rates in urban canyon (Makokha and Shisanya 2010a, 2010b). Moreover, urbanisation is a dynamic issue hence the effects of land cover changes studied today will be different when the study is done in future time. It is therefore clear from individual case studies that there are significant differences in urbanisation processes among regions and countries, and even within countries. Moreover, urbanisation as a physical phenomenon is not a homogeneous process (Seto et al. 2011).

Urban development therefore brings about changes in the physical behaviour of the landscape, affecting its hydrological, thermal, radiative and aerodynamic properties, which in turn affects the exchange of heat, mass and momentum between the surface and the atmosphere (Jansson 2006; Cui 2005). Flash flooding effects can also be experienced in densely built-up environments if there is no proper mechanism to facilitate drainage system as the city continues to expand (Douglas et al. 2008).

2 Bioclimatic indices for thermal comfort

Thermal comfort is the mental condition that expresses satisfaction with the thermal environment. Assessment of human bioclimatological comfort sensations in different urban environments has been done using bioclimatic thermal indices. In human bioclimatology, a large number of indices can be found, but it is advised to use the indices developed basing on the concept of human body energy balance. Such indices especially those incorporating the four main meteorological elements namely air temperature, air humidity, wind speed and radiation fluxes can be applied universally.

In this class of indices, it has been found that the physiologically equivalent temperature (PET) is the useful bioclimatic index to use. Additionally, PET uses a usual and widely known unit of degree Celsius as an indicator of thermal stress (Deb and Ramachandraiah 2010) and evaluates the thermal conditions in a human physiological manner (Mayer and Höppe 1987; Matzarakis et al. 1999; Höppe 1999). The unit is commonly known to other people who do not necessarily be human biometeorology professionals. PET can also then be applied in different climates and all year round (Matzarakis et al. 2007; Lin and Matzarakis 2008; Zaninovic and Matzarakis 2009; Gulyás and Matzarakis 2009, Çalışkan et al. 2012). The index has already been used to assess human bioclimate in cities of hot–humid climate in Southeast Asia (Johansson and Emmanuel 2006; Emmanuel et al. 2007; Lin et al. 2010). PET is therefore 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

(Deb and Ramachandraiah 2010;Mayer and Höppe 1987; Matzarakis et al. 1999; Höppe 1999).

The emergence of universally applied bioclimatic indices can be traced back to Fanger's predicted mean vote model in 1967. The model was developed basing on thermoregulation and heat balance theories (Fanger 1972). The theories assert that the human body employs physiological processes so as to balance the metabolic heat energy produced by the body and the heat lost from the body (Orosa 2009). Together, with PET, other universal thermal indices include the recently developed Universal Thermal Climate Index (UTCI; Jendritzky et al. 2012), perceived temperature (Staiger et al. 2012), and the modified Standard Effective Temperature. The latter two indices together with PET have been compared with UTCI and they were found to performance comparably (Blazejczyk et al. 2012). This is because all of these indices take a similar approach (Staiger et al. 2012). In the current thermal bioclimate analysis for Dar es Salaam, PET was preferred to the other, since it runs smoothly in the RayMan model and has been used for a quite a long time hence been critically examined in different environments of the world (Matzarakis et al. 2007, 2010; Lin 2009, Farajzadeh and Matzarakis 2012).

In Dar es Salaam, Nieuwolt (1973) used hourly datasets of air temperature and humidity for 1968–1971 to assess the thermal comfort and found Temperature Humidity Index (THI) above 25 °C during afternoons from October to May. At 24 °C, most people would start to experience thermal stress according to THI thermal scale based on experiments done in the USA. In a neighbour country of Kenya, spatial, seasonal and diurnal variation of the Effective Temperature (ET) index was determined by using meteorological data for the period of 1968–1988 for the purpose of classifying the country into climatic comfort zones (Makokha 1998). Like THI, ET also is determined by using air temperature and relative humidity and has been widely used especially in places where other parameters are unavailable (Makokha 1998; Jauregui 1991). It is then apparent that the two indices could not comprehensively address the human body heat balance due to lack of the other meteorological elements of wind speed and radiation. The use of PET will then sufficiently give a detailed thermal comfort assessment of the urban environment of Dar es Salaam city. Whereas in the tropical Africa area, PET has already been applied to study the effect of thermal environment on the occurrence of measles in Ondo state, Nigeria where it was found that together with UTCI, PET correlates well with the transmission of measles (Omonijo et al. 2011). Recently, Eludoyin and Aldelekan (2012) have employed three indices of ET, THI and RSI (relative strain index) to study the physiologic climate of Nigeria and found that the indices can provide complementary information regarding the thermal stress assessment.

The study of the urban climate and bioclimate of Dar es Salaam is very important not only because of the growing concern for environmental quality and energy conservation among policy makers, architects, engineers and planners but also to the general public in ensuring a quality of life among the urban dwellers. Dar es Salaam at the moment constitutes of over 70 % of unplanned settlements and efforts for restructuring and redeveloping such settlements are undertaken (UN HABITAT 2010). It is also equally important to carry out adequate study of the climate of any specific site in order to enhance cross-continental transfer of architectural and engineering ideas from temperate areas to the tropics. The study of urban microclimate created a bridge that links climatology research and applied urban design. This provides architects and urban planner imperative climatic information of how microclimatic conditions in the space between buildings can be affected by the built environment at all scales, and analyses the interaction between microclimate and each of the elements of the urban landscape.

Moreover, urban climate research seems to be inevitable today as the world is experiencing a tremendous demographic transition from rural to urban (UN HABITAT 2008). In 2007, half of the world's population lived in cities and it is projected that within the next two decades, 60 % of the world's people will reside in urban areas than in other types of settlements, the trend is expected to continue for the foreseeable future (UN HABITAT 2008). While, the world is still constrained by the effects of climate change of which its impacts in developing countries are high due to poor adaptive capacity, less urban climate research is being conducted there. The use of best urban planning practices that incorporate the knowledge of urban climate is important especially in enhancing urban poor to cope with climate change.

The aim of the present paper was to assess the human biometeorological conditions of Dar es Salaam by applying the relatively universal thermal index of PET. The objectives formulated in order to achieve this aim include the use of easily available synoptic meteorological data sets to evaluate the human thermal background conditions of the city. Secondly, to apply the concept of frequency of occurrence in assessing the human thermal stress conditions as well in determining the local micrometeorological conditions of the city basing on the same background condition. The problem of meteorological data availability in many tropical cities in developing countries is known (Jauregui 1991), thus, the current study has to rely on information from one synoptic meteorological station in order to provide important insight of tropical urban climate of a coastal city in southern hemisphere. However, the present results are treated as the first results of the ongoing study, and they provide a focus on the future study of understanding the climatic impacts of land cover changes on microclimate and human thermal bioclimatic conditions of a coastal town in low latitude, just south of equator.

3 Research methodology

3.1 Study area

The focus of the study is Dar es Salaam city in Tanzania (Fig. 1). Dar es Salaam is the largest and leading economic city in Tanzania with an estimated population (in 2010) of 3.1 million people (NBS 2011). Historically, Dar es Salaam grew from a small sea port and trading centre of 900 people in 1867 to a city of 2.49 million inhabitants in 2002 (NBS 2006).

Dar es Salaam is located at 6°51′S, 39 18′E along the south-western coast of the Indian Ocean (Jonsson et al. 2004). As a region, Dar es Salaam covers an area of 1,393 km^2 of land mass including eight offshore islands (DCC 2999). The region is administratively divided into three municipalities of Kinondoni, Ilala and Temeke, together composing of 73 wards. The whole region is considered as urban (UN HABITAT 2010).

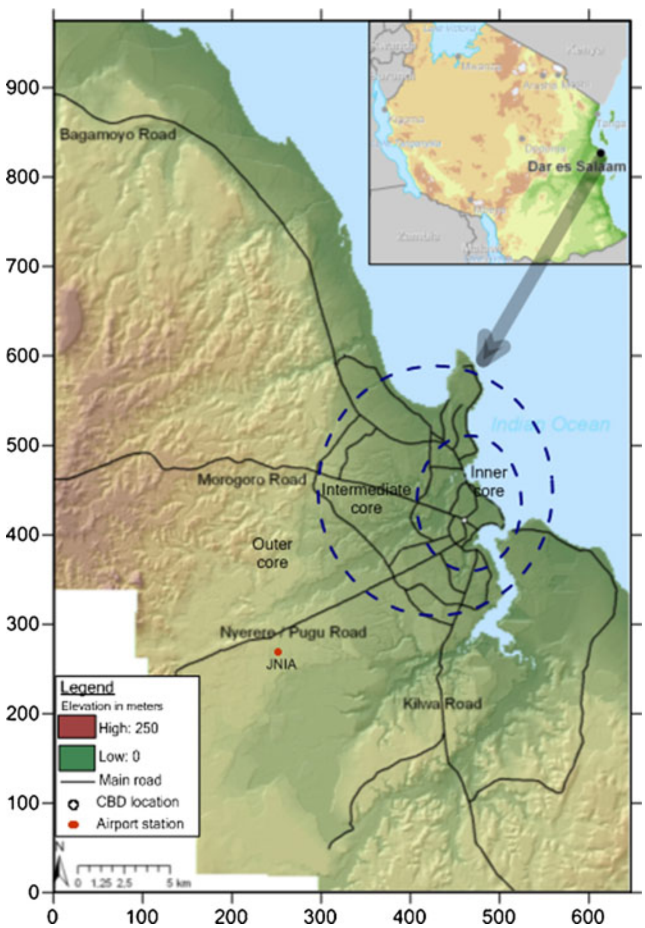

Fig. 1 Map of Dar es Salaam indicating the location of the synoptic station (Julius Nyerere International Airport) and the concentric circles to demarcate urban growth in zones from its central business district. Source: Modified from Hill and Lindner (2010)

3.2 Urban structure

Due to its location along the coast and the existence of the four main roads entering the city, Dar es Salaam city has been observed to expand in a radial structure. The radius increased from 2 km in 1945 to about 18 km in 1991. In 2002, the radius extended to 32 km to the north along Bagamoyo Road, 28 km westwards along Morogoro Road, 20 km along Pugu (now Nyerere) Road, and 14 km along Kilwa Road to the south. Human settlements are also influenced by the existence of roads as an important infrastructure.

Currently, the city is under redevelopment projects steered in partnership between the government and the UN HABITAT to reduce the area of unplanned settlements. Generally, the city structure can be briefly described into three concentric cores from the city centre, namely the inner, intermediate and outer cores as indicated in Fig. 1.

Within the inner core, the city centre consists of the two famous business areas of Kariakoo and Posta which may be regarded to form the central business district of Dar es Salaam. The Mnazimmoja garden which separates the two business areas, serves a great role of amelioration with its greenery scene. The area of the inner city is approximated to 200 km^2. Most of the streets are narrow and asphalt constructed. The streets in the Posta area are planted with trees along and the area is greener due to the presence of golf grounds of Gymkhana and the botanical garden. Tree species include *Delonix regia* (Christmas tree), *Polyalthia longfolia* (Ashock tree) and *Azadirachta indica* (Neem tree). Buildings in this core are high and medium rise. In the last 10 years, construction of high-rise buildings has been undergoing at a high rate hence increasing the number of buildings with more than 10 storeys. Separating the inner core and the intermediate core is the Jangwani valley along Msimbazi River which also acts as the flood plain.

The intermediate core is mainly a residential with some few light industries like breweries and textiles. Most streets and roads are also asphalt constructed. Due to its mix nature of residential and industry, few high- and medium-rise buildings can still be located. Some places can be classified as open-set high rise and compact low rise in respect to Stewart and Oke (2010) local climate classification. Green spaces can be located as gardens on homes and light industries' premises. The Msimbazi River that extends from the Jangwani valley continues to save as a flood plain with some green spaces accompanied by intensive urban agriculture (Howorth et al. 2001). The ring like circuit formed by the Mandela highway and Sam Nujoma road can be considered as a virtual boundary, separating the intermediate core from the outer core.

In the outer core especially southwards in Kigamboni and Temeke, there is more palm trees and other plantations especially in the sub-urban areas. More green and water spaces can be realised due to the presence of the Pande forest reserve to the northwest and the Kizinga and Mzinga valleys to the south. Though Pande is a small forest reserve, it serves a significant portion of green space in the study area. Mainly low rise buildings and industries including the Julius Nyerere (formerly Dar es Salaam) International Airport are within this zone. A range of climate classes according to Stewart and Oke (2010) classification can be located. These include open-set mid-rise, extensive low-rise, high-energy industrial and sparsely built. However, a full classification of climate zones in an urban area can best be achieved with the help of more information like sky view factor, building surface fraction, mean building height, anthropogenic heat flux and natural surface fraction.

4 Climatic conditions over Dar es Salaam

In general, Dar es Salaam is lowland with a typically hot–humid climate. The climate of the area is greatly influenced by the northeast monsoon which prevails from the months of March to October and the southeast monsoon between October and March (Jonsson et al. 2004). This is in response to the passage of the Inter-tropical convergence zone. In describing the climatology of Dar es Salaam, together with existing literature, monthly meteorological datasets from the synoptic station at the Dar es Salaam airport for the period 1974–2008 were also used for this purpose.

Figures 2 and 3 summarise the climatological situation in terms of local winds, air temperature and rainfall. The local winds are generally gentle to moderate between 4 and 6 m/s during the afternoons where the highest monthly winds are experienced in August and the afternoons of March to April recording the lowest speeds (Fig 2a). The weak winds in March and April is mainly attributed to the fact that this is the period where much of the rainfall occur and it is presumably that there is no high differential surface heating between the land and the sea for the effective local sea–land breeze system at this period (Nieuwolt 1973). The climate of Dar es Salaam is also greatly influenced by the sea due to its proximity to the Indian Ocean. This makes Dar es Salaam and other coastal towns in the country to experience high air temperature and humidity almost throughout the year.

Air humidity in Dar es Salaam ranges between 67 and 96 % for a year, with April being the most humid month. The annual rainfall is about 1,050 mm and it usually peaks in April and December. This signify the two rainy seasons of short rains (October–December season) with an average of 75–100 mm per month and long rains (March–May season) with a monthly average of 150–300 mm per month of rainfall (Howorth et al. 2001). The mean annual temperature is therefore about 30 °C with a slight seasonal change in temperature due to its proximity to the equator. The mean daily sunshine duration is about 10–12 h per day.

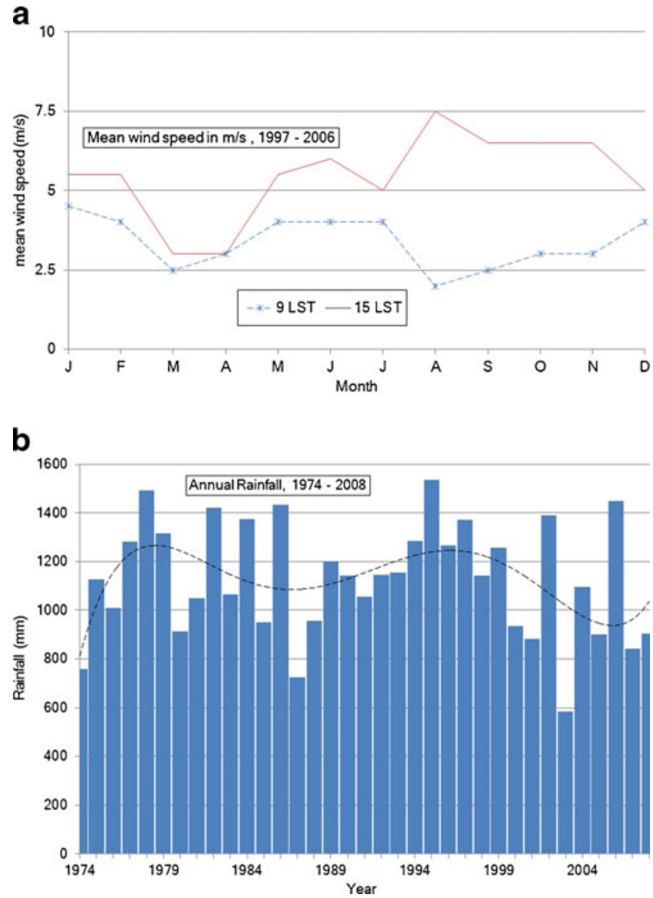

Fig. 2 **a** Mean local wind speeds at 09:00 and 15:00 hours LST basing on 10 years data from 1997 to 2006. **b** Annual rainfall trend for the measuring period 1974–2008, data from the airport station, Dar es Salaam city

In general, the climate of Dar es Salaam can therefore be described using the Köppen classification system as a tropical wet/dry climate (Roth 2007). It means there are distinct wet and dry periods of the year. The wet period stretching from late October to December and from March to May while the dry period prevailing in the rest of the months. This implies that seasonality is the basic important characteristic of climate classification in tropics according to the Köppen system. In terms of temperature, it is rather warm from late September to April and cool from May to August.

4.1 Meteorological data

The calculation of thermal indices can efficiently be facilitated through the use of small-scale applied bioclimatic

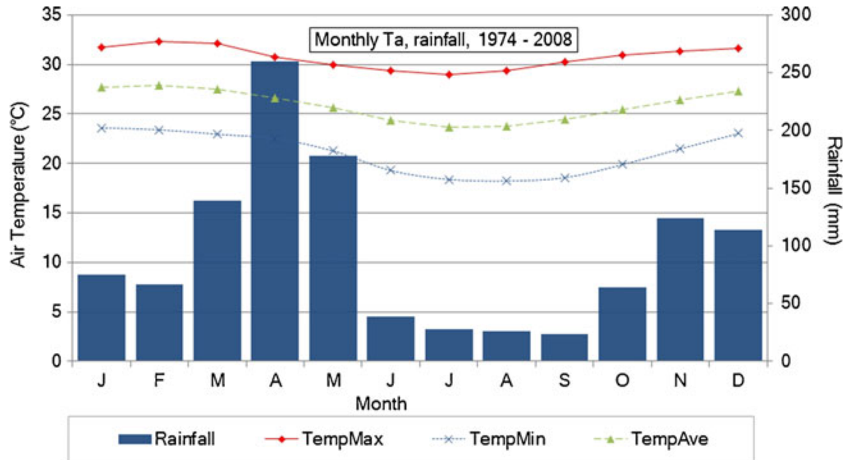

Fig. 3 The climatology for Dar es Salaam in terms of air temperature and rainfall as analysed using data from the airport synoptic station (1974–2008) and the range of the mean extreme temperature for each month of the year

modelling software like RayMan (Matzarakis et al. 2007, 2010), ENVI-met (Bruse 1999, 2004) and Solweig (Lindberg et al. 2008). The availability of these small-scale urban climate models saves much of the time to calculate the individual indices. All of the calculations in this study were done in RayMan model. RayMan was developed and is maintained by the Albert-Ludwigs University Freiburg. It is freely available online to the community of applied climatology to make use of it (http://www.urbanclimate.net/rayman/). The model has the advantage that it facilitates reliable determination of the microclimatological modifications of different urban environments as it considers the radiation modification effects of the complex surface structure (buildings, trees) very precisely. Apart from other data inputs in accordance to the human body heat energy balance, meteorological input parameters include air temperature (in degree Celsius), relative humidity (in percent), wind speed (in metre per second) and global radiation (in watts per square metre). In this study, global radiation was estimated by the model basing on the input data of cloud cover. The synoptic meteorological data observed at 3-h interval at the Julius Nyerere International Airport, Dar es Salaam were obtained freely from the Ogimet website. Before use, the datasets were decoded from its Synop code and the errors associated with wrong codes were corrected.

Additionally, various datasets from other secondary sources were also used to analyse the micrometeorological conditions of Dar es Salaam. The data sets include monthly (maximum and minimum) air temperature from 1974–2006 which also include some daily values (maximum and minimum) from January–May 2006. Rainfall datasets included daily rainfall (October 1997–May 2002 and January–May 2006), rainfall records in dekads (1978–2007) and monthly rainfall (1974–2008). For the case of relative humidity, daily datasets for January–May 2006 period and monthly wind speeds recorded at 09:00 and 15:00 hours local standard time (LST) from 2002 to 2006 were used. In addition, the data extracted from the wind patterns summary of 10 years from 1997 to 2006 were incorporated and was found quite useful in comparing with the analysed wind frequencies by wind roses which utilised synoptic wind data of 2001–2011. Although the current study employed data from the synoptic station at the airport, further study on the urban climate of Dar es Salaam can be facilitated by data from other stations within Dar es Salaam and nearby areas with meteorological stations as highlighted in Table 1.

5 Results

The preliminary results provided in this study are about the urban climate and bioclimate of Dar es Salaam city in Tanzania. The results are considered preliminary in the sense that more work is still being carried on for the purpose of understanding the impacts of land cover changes on the microclimate of the Dar es Salaam city which is growing fast and in particular urban sprawl. Synoptic data from one station were used in order to give an overview of meteorological conditions and the thermal biometeorological conditions of the city using the PET thermal index.

5.1 Meteorological conditions

Analyses of individual meteorological parameters which influence the PET was done for the purpose of understanding the diurnal course of the meteorological conditions. Analysis of meteorological conditions is imperative in order to render meaningful interpretation of thermal comfort from the PET index. Such analyses include air temperature, relative humidity, vapour pressure, cloud cover and wind field. The analyses for air temperature, relative humidity, vapour pressure and cloud cover was done only for the datasets of year2007 to account for the diurnal evolution while that of the wind field used the whole 2001–2011 dataset which include seasonal analysis.

Table 1 Status of available meteorological station infrastructure in Dar es Salaam city and its surrounding areas

Station name	Location (latitude/longitude)	Elevation (m)	Type of station	Weather elements observed/measured
Julius Nyerere International Airport (airport)	06°52′S/39°12′E	53.0	Synoptic	All synoptic weather elements
Dar es Salaam Univ.	06°47′S/39°12′E	92.0	Climatological	Rainfall
Wazo hill	06°40′S/39°10′E	111.0	Climatological	Rainfall
Port Met.	06°50′S/39°18′E	50.0	Sea station	Screen elements, sea information
Staki Shari	06°52′S/39°11′E	N/A	Climatological	Rainfall
Dar es Salaam Lab.	06°49′S/39°18′E	9.0	Climatological	Rainfall
Kibaha	06°50′S/38°58′E		Climatological	Screen elements
Kisarawe	06°54′S/39°04′E	274.0	Agroclimatological	Rainfall
Bagamoyo Agric.	06°25′S/38°55′E	9.0	Agroclimatological	Rainfall

5.1.1 Air temperature pattern

Figure 4a shows the diurnal pattern of air temperature analysed in classes of 5 °C interval. The results indicate that minimum air temperatures of below 20 °C are less frequent in a year, but they occur only between 03:00 and 06:00 hours LST. While, the high air temperatures of the range 30–35 °C have a high preference of occurrence during the afternoons between 12:00 and 15:00 hours LST. There is however a low frequency of occurrence of extreme temperatures of above 35 °C, particularly at around 15:00 hours LST.

5.1.2 Relative humidity pattern

The abundance surface moisture supply from the ocean coupled with nearly constant high air temperature leads to the observed high relative humidity in Dar es Salaam. However, marked diurnal variation of the relative humidity

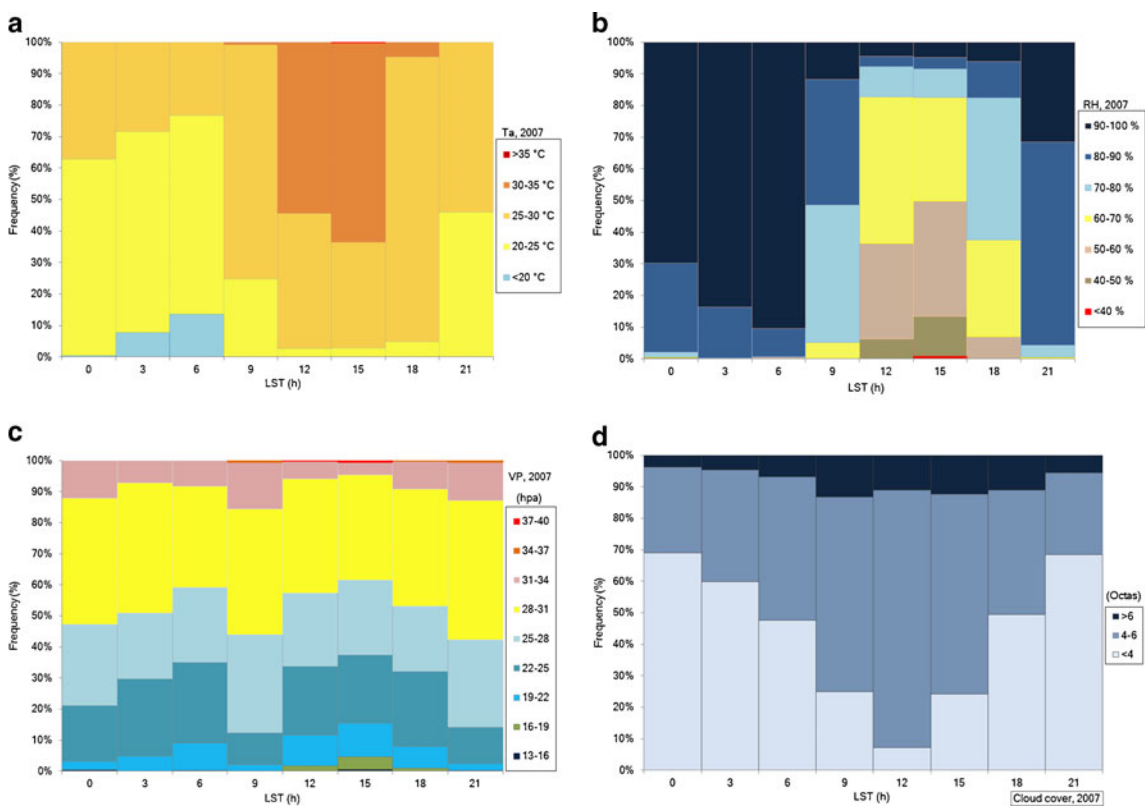

Fig. 4 Diurnal course of meteorological parameters in terms of classes for the 2007 datasets of air temperature (**a**), relative humidity (**b**), vapour pressure (**c**) and cloud cover (**d**)

can still be observed as illustrated by classes of 10 % interval of relative humidity in Fig. 4b. It should also be noted that normally the diurnal cycle of relative humidity fluctuates between maximum near the dawn and a minimum around early afternoon. Now, in Dar es Salaam, the results indicate that frequency of moisture stress of RH below 40 % is very low and can mostly occur at around 15:00 hours LST. However, the minimum relative humidity was observed to be mostly contained within the classes of 50–60 and 60–70 % in the afternoon periods. On the other hand, a noticeable very high frequency of occurrence of RH above 90 % was observed from 21:00 hours LST with a peak just before sunrise at 06:00 hours LST. Meaning, the maximum relative humidity in Dar es Salaam is almost always above 80 % throughout the year. The overall observed relative humidity pattern seems to clearly signify the thermal effect on relative humidity.

5.1.3 Vapour pressure pattern

Relative humidity is usually referred to as a sensitive function of temperature while vapour pressure is a direct measure of moisture content, albeit both indicate the presence of moisture in the atmosphere. Vapour pressure can hold less water vapour at the low temperatures than at high temperatures. The vapour pressure pattern in terms of the frequency of occurrence was analysed in classes of 3 hPa interval as shown in Fig. 4c. The pattern clearly indicates that on daily basis, the extreme vapour pressure of between 37 and 40 hPa occurs rarely between 12:00 and 15:00 hours LST with only 0.1 % of occurrence while the lowest vapour pressure between 13 and 16 hPa can occur only during the afternoon at 15:00 hours LST also at 0.1 % of occurrence. The pattern indicates further that throughout the day, the vapour pressure in Dar es Salaam is frequently within the three classes of vapour pressure grouping of 22–25, 25–28 and 28–31 hPa, though the 28–31 hPa class is relatively the most dominant with nearly more than 30 % of occurrence throughout the day. Probably, the pattern also suggested a slight change on the daily course of vapour pressure pattern at 09:00 hours LST where a 0.1 % of occurrence for the 34–37 hPa class reappears. The changes could also be interpreted that there is increasing of convection just after 09:00 hours LST with its maximum at 15:00 hours LST where the full range of vapour pressure classes are also realised.

5.1.4 Cloud cover pattern

The cloud cover pattern was classified into three classes of less than four octas, four to six octas and above six octas, simply defined as clear, partly cloudy and cloudy conditions respectively. It is important to note here that the above classification of cloudiness is employed to assist in the analysis and interpretation of the present results only. It should not be regarded as a standard classification. Other studies have also used the idea of classifying cloudiness in order to ease the analysis and interpretation of cloudiness (Emmanuel and Johansson 2006). For this case, using the 2007 dataset, Dar es Salaam is generally observed to attain a maximum frequency of cloudiness occurrence around the noon time and decreases as one approaches the midnight (Fig. 4d). This pattern displays a true characteristic of the tropical location near the equator.

5.1.5 Wind pattern

The frequency distribution of the wind was done in order to understand the prevailing wind conditions in Dar es Salaam. The 11-year datasets from 2001 to 2011, collected at the airport station, were used. As the temporal analysis, the results show that wind is northerly and partly south-westerly during the morning hours (around 06:00 hours LST). The wind distribution was later observed to shift to more of north-easterly and south-easterly during the afternoon (Fig. 5).

A further seasonal analysis of wind distribution was done in the respective individual four seasons of the year (Fig. 6). In this case, it is noted that wind is more northerly to north-easterly in the DJF season and shifting to southerly and south-easterly in the MAM season. During the cool season of JJA, winds are still mainly southerly and south easterly changing to easterly in the SON season.

5.2 Bioclimatic conditions (thermal comfort)

Calculations of bioclimatic indices of PET were done in the RayMan software in order to give a situation of human bioclimatic condition in the context of human thermal comfort (Matzarakis et al. 2007, 2010). Then, the human biometeorological evaluation was done on the basis of the frequency of occurrence of thermal stress in terms of PET classes. The PET classes are fully described in Table 2.

5.2.1 PET pattern

For the purpose of better understanding, the human thermal biometeorological condition of Dar es Salaam, the PET index was used which requires air temperature, air humidity, wind speed and radiation fluxes as its meteorological input parameters. It is especially important for the human bioclimate assessment in such a coastal tropical city to consider a universal thermal index like PET, whereby previous assessment have relied on air temperature and relative humidity thermal indices. The calculation of PET values had however to use the radiation flux estimated from cloud cover data due to unavailable record of former meteorological data in the

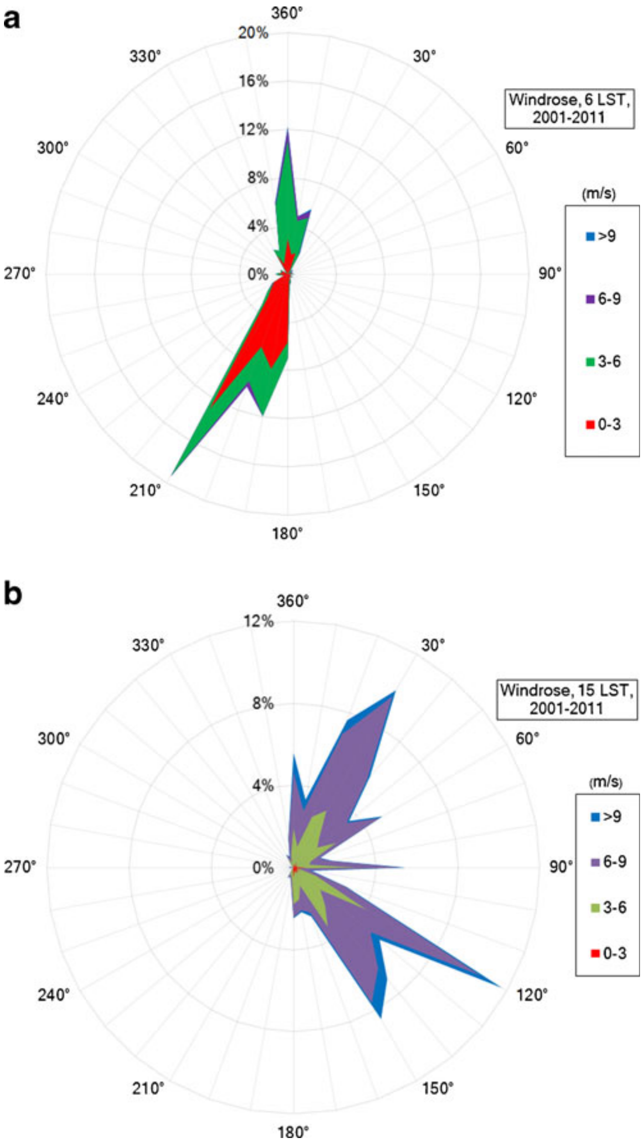

Fig. 5 Frequency distribution of wind field during the morning (**a**) and later in the afternoon (**b**)

available synoptic data. In order to have all these four inputs, some of the records have missing values in the corresponding parameters hence such records were removed completely. Due to elimination of data records with corresponding missing values in some meteorological elements, analysis to discern the diurnal cycle of PET was done using the 2007 datasets alone as it has relatively fewer missing values compared to the other years (2001–2011).

Frequency analysis in terms of PET classes was then done at 06:00, 15:00 and 18:00 hours LST so as to quantify the background conditions of thermal comfort using the airport station as a representative for the background conditions to be experienced in the coastal city of Dar es Salaam. Comprehensive human thermal comfort conditions as depicted by the PET index are fully detailed in Figs. 7 and 8. Figure 7 gives the general mean monthly conditions in terms of 10 days duration at 06:00, 15:00 and 18:00 hours LST while Fig. 8 describe the diurnal course of human thermal conditions in terms of the observed synoptic hours interval. Figure 7 generally indicated that strong heat stress of above 35 °C of PET prevail the afternoon period, especially from October to April with about 50 % of occurrence. During sunrise, slight warm temperature can be experienced from October to April with some slight cold stress in June and August (Fig. 7a) with only up to 10 % of occurrence. In the evenings, the PET pattern suggests a low frequency of occurrence of about 10 % of moderate human thermal stress (29–35 °C of PET) in February to March (Fig. 7c).

On the other hand, the seasonal cycle of the diurnal cycle indicated that PET ranges from 22 to 37 °C in the DJF season and from 15 to 32 °C in the JJA season. The seasonal peak appears to occur earlier in day during MAM at around noon time and late in DJF season at around 15:00 hours LST (Fig. 8a). However in Fig. 8b, it is surprising to observe thermal stress of PET >41 °C starting to occur more frequently from late morning at around 09:00 hours LST and diminishing progressively later in the afternoons. Nonetheless, noon time is experienced with high frequency of thermal stress of PET >35 °C, followed by late afternoons. Further, in accordance to PET classes, moderate cold stress (PET between 8 and 13 °C) is occasionally experienced in early morning hours around 06:00 hours LST.

6 Discussion

The first part of our results describes the analysis of individual meteorological parameters. The diurnal cycle of air temperature, relative humidity and cloud cover are observed to display a true characteristic of a location in the tropical coast. Dar es Salaam is considered to be hot since the frequency of air temperatures greater than 25 °C is high. The effect of air temperature can also be observed on other parameters like relative humidity and local wind system.

The results however indicate a low frequency of occurrence of extreme air temperatures of above 35 °C. This low frequency of occurrence of air temperatures of above 35 °C corroborates the earlier observation of high air temperatures of above 35 °C at both Kurasini and Airport weather stations in Dar es Salaam (Bargman 1970). The diurnal cycle of minimum air temperature occurring before dawn and maximum temperature in early afternoon also agrees well with the earlier climatic studies of Dar es Salaam city (Bargman 1970) as well with that of other hot–humid cities in the tropics like in Colombo, Sri Lanka (Johansson 2006).

It is clear from the relative humidity frequency analysis that from 21:00 to 09:00 hours LST, relative humidity is

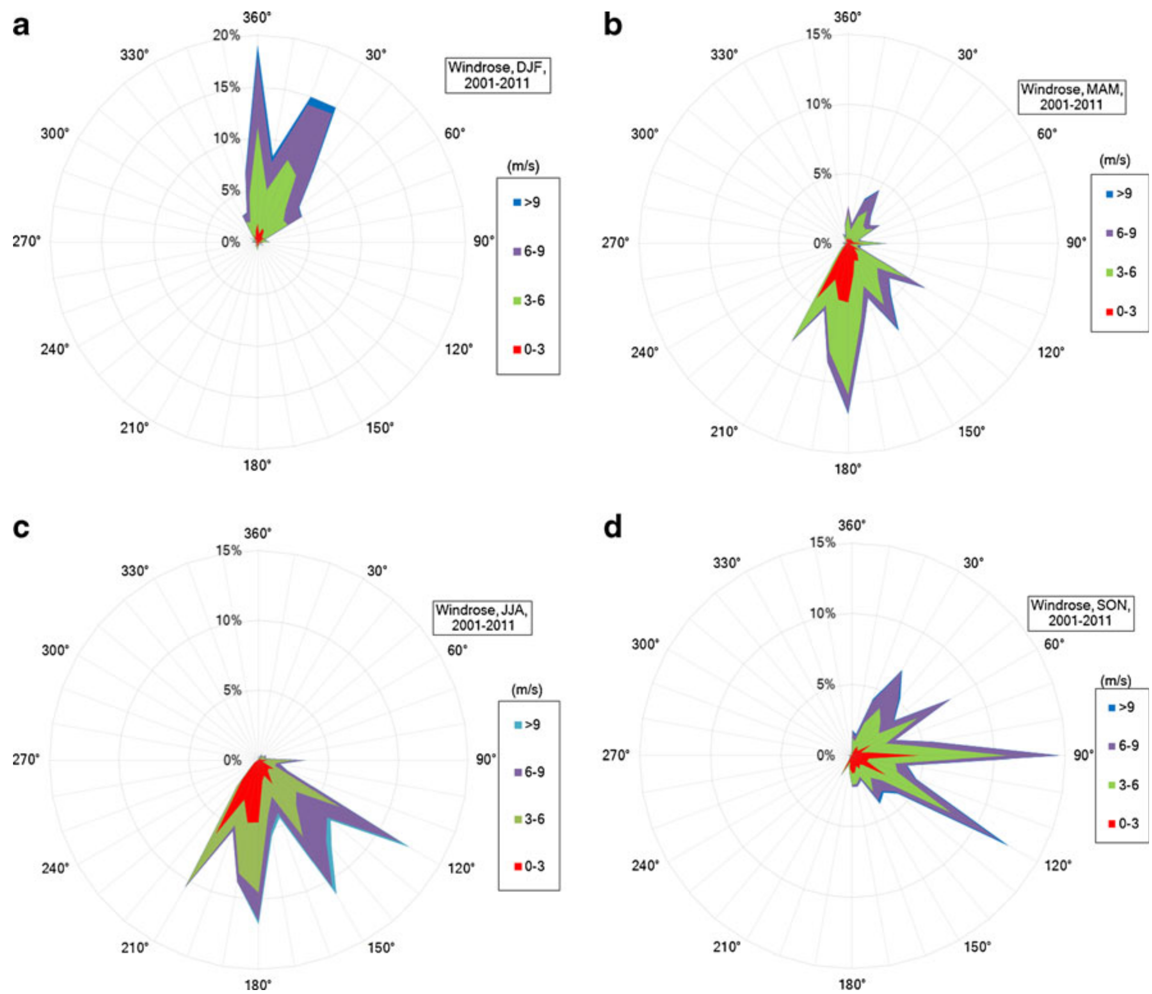

Fig. 6 Frequency distribution of wind field in different seasons of the year, DJF (**a**), MAM (**b**), JJA (**c**) and SON (**d**)

above 60 %. Earlier studies also reported Dar es Salaam to be a humid all year round (Bargman 1970; Jonsson et al. 2006). The time of moisture stress of less that 40 % of RH in our results, also corresponds well with the reported occurrence of minimum relative humidities at Kurasini and Airport station at 15:00 hours LST which is also the time of maximum air temperature occurrence (Bargman 1970).

Table 2 Full description of the PET class with their corresponding thermal perception. For more detailed description, see Matzarakis et al. (1999)

PET class	Thermal perception	Physiological stress
<4	Very cold	Extreme cold stress
4–8	Cold	Strong cold stress
8–13	Cool	Moderate cold stress
13–18	Slightly cool	Slight cold stress
18–23	Comfortable	No thermal stress
23–29	Slightly warm	Slight heat stress
29–35	Warm	Moderate heat stress
35–41	Hot	Strong heat stress
>41	Very hot	Extreme heat stress

The amount of moisture present in the air can be a function of the moisture content, cloudiness, air temperature, wind and vegetation. But, generally, tropical cities are observed to be very humid (Adebayo 1991). Dar es Salaam is very humid since it is close to the sea. Normally, on-shore winds act as moisture supply while the off-shore winds drive moisture towards the sea. The wind analysis indicates that day time is dominated by sea breezes. However, in the analysis, it is clear that minimum humidities occur at the time of maximum temperature, usually during the early afternoon and maximum humidity occurring around the dawn as temperatures also tend to be low. This pattern is also revealed in other studies done in tropic cities. Adebayo (1991) found the annual mean of relative humidity for Ibadan, Nigeria (200 km north of Atlantic Ocean) ranged between 79 and 83 % at 09:00 hours LST and between 57 and 74 % at 15:00 hours LST, with a less seasonal trend. In

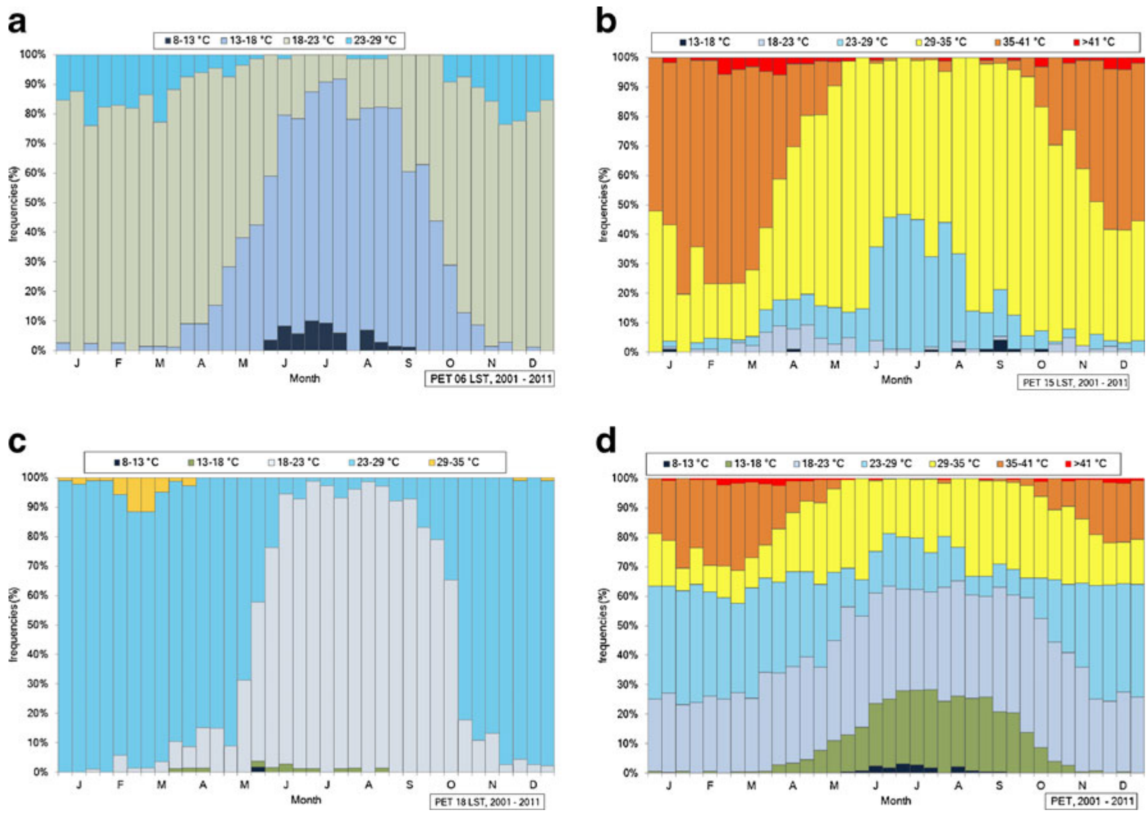

Fig. 7 Frequency of occurrence of different thermal stress as indicted by PET classes at different hours (local time) of the day in a year, starting at 06:00 hours LST (**a**), 15:00 hours LST (**b**), 18:00 hours LST (**c**) and all hours combined (**d**)

addition, the dipping of the vapour pressure pattern at around 9:00 hours LST is due to the increased frequency of occurrence of vapour pressure in the classes of 25–28 and 28–31 hPa with decrease in frequency for the lower classes. At the same time, though with low frequency of occurrence, a 34–37 hPa class of vapour pressure emerges. This sets as a transition to high vapour pressures dominating the afternoons hence suggesting high convection during that time.

The cloudiness pattern was generally observed to be cloudier during the afternoons than the other times of the day. The cloud climatology of a coastal location can be complex due to influence of maritime meteorology. Normally, clouds over the sea or a location very close to the sea tend to build up at and after dawn and persists until mid-morning at which time it clears away. However, the location where observations are made is about 12 km from the coast and in an inland tropical location, the early morning tends to be clear with cloud forming by mid-day and developing during the afternoon followed by rapid clearance in the evening. This is probably why the frequency graphs indicate the maximum occurrence of clouds at around noon. Dar es Salaam may seem to be cloudy all the year round with main clouds being the cumuliform (Bargman 1970) and this may have effect on sunshine duration, length of the day and relative humidity.

It was actually not surprising to observe the non-existence of the pure westerly component on the wind pattern analysis in Dar es Salaam. The analysis was done with 10 m wind data and a perhaps a good explanation for this rely on the fact that the coastline in Dar es Salaam runs nearly in a northwest to southeast orientation. This subjects the local winds to blow almost at right angles to the coast (Nieuwolt 1973). The earlier study, though, used only 4 years data from 1955 to 1958 indicating no significant change of the orientation of wind direction with the current results (Nieuwolt 1973). Other studies have also observed the frequency of occurrence and cumulative distribution of the maximum wind speeds in Dar es Salaam to be more influenced by coastal winds unlike the other Tanzanian coastal towns of Tanga, Zanzibar and Mtwara which were found to be mostly influenced by offshore winds. In addition, weak winds prevail in Dar es Salam while the strongest winds were observed in Mtwara (Dubi 2001). Analysis of wind patterns is important for urban human bioclimate of Dar es Salaam as this information suggests that the thermal human bioclimate condition could be greatly modified by prevailing wind conditions which mostly originate from the sea. For instance, the persistence of sea breeze in Funchal was found to be an important factor to improve thermal comfort (Lopes et al. 2011).

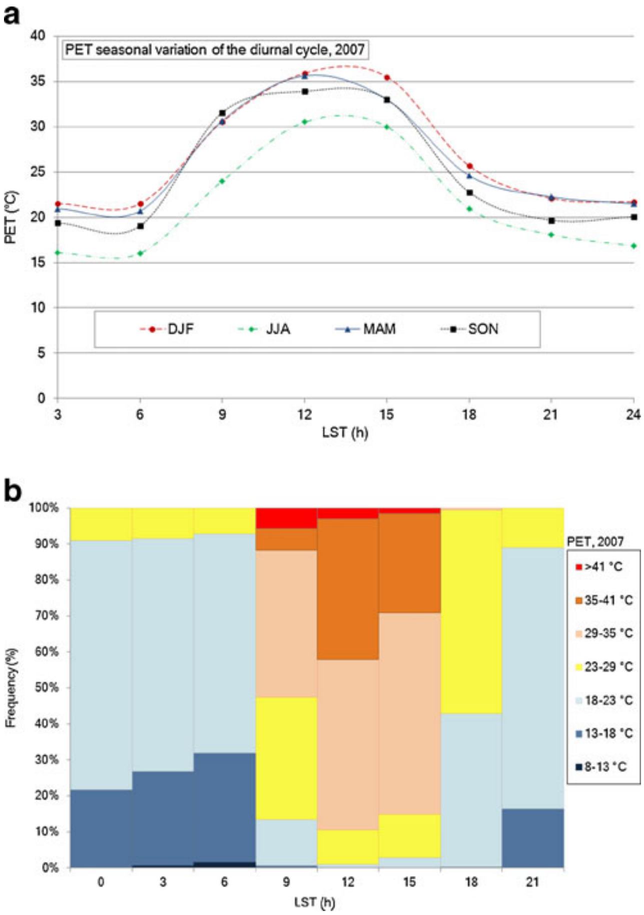

Fig. 8 Diurnal cycle of PET in different seasons of the year as shown by the **a** and the diurnal variation of PET classes to indicate the frequency of occurrence of different thermal stress in a day **b** using the data for year2007

In a nutshell, many meteorological parameters in tropics exhibit strong diurnal variation compared to seasonal ones. This observation is also apparent in our analysis of the individual weather elements and is firmly confirmed in other tropical urban studies in Africa (Nieuwolt 1973, Akinbode et al. 2008, Adebayo 1991, Makokha & Shisanya 2010a).

The second part of our analysis is about thermal comfort in Dar es Salaam. The results indicate that afternoon time is the most uncomfortable period of the day with PET above 35 °C. This coincides with the maximum air temperature of the day where the relative humidity is also observed to be the lowest. Of the seasons, DJF is the most uncomfortable season while JJA is relatively comfort. This result also correlates well with the earlier study where THI values were observed to be high from December to March (Nieuwolt 1973). However, THI uses only air temperature and relative humidity and the use of PET is seen as an improved kind of human discomfort assessment. PET uses more input parameters based on the human heat energy balance.

The seasonal analysis also suggest that during the day, PET values are above the comfort limit (24 °C) just from 07:00 to 18:00 hours LST in the SON, DJF and MAM seasons while in JJA starts at least later at 09:00 hours LST and lasts up to 17 hours LST. Probably an improved PET class limits can be thought depending on the thermal adaptation of people. However, high values of PET exceeding the comfort limit has been also found in other tropic city of Salvador, Brazil (13° south) where season PET values were above upper comfort limit throughout the year around midday from about 10:00 to 16:00 hours LST (Andrade et al. 2004).

In the analysis of the daily cycle of PET using the 2007 dataset, results indicate that the extreme heat stress may occur frequently at 09:00 hours LST and progressively decreasing till 15:00 hours LST (Fig. 8a). This result is rather surprising as generally heat stress of PET between 35 and 41 °C is high at around 12:00 and 15:00 hours LST. Perhaps, the effects of relative humidity play a great role as it was observed to be at its lowest amount during the afternoons. Nonetheless, the general diurnal course of PET coincides well with other thermal bioclimate studies done in the hot and humid climates though minor differences in terms of the extent of thermal stress can still exist. In Colombo, Sri Lanka, Johansson and Emmanuel (2006) found that PET values during the day are above the suggested upper comfort zone limit of 33 °C and far exceeded this limit during the period 11:00–16:00 hours LST; hence, the thermal comfort is obviously very poor. Whereas in Morocco city of Fez (hot and dry), extremely high PET values exceeding 40 °C were observed between 11 h and 17 LST in the summer (Johansson 2006). The extremely high daytime PET value is attributed to the exposure of direct solar radiation.

In this study, 11-year synoptic datasets were used to assess the biometeorological conditions in Dar es Salaam with PET as the sole human biometeorological index. It is likely that an improved assessment of human biometeorological condition can also be achieved by use of high temporal resolution data sets probably at hourly interval. In addition, weather forecasts in tropics especially at a coastal location can be greatly improved when a component of human discomfort condition can be included instead of the traditional maximum and minimum air temperature alone. Such a forecast in terms of discomfort index will actually incorporate the effects of humidity which is likely to be high and probably greatly influencing the thermal sensation of the people. As an individual weather element, it is probably rainfall perceived to have a direct effect on daily life to most people in tropics. Then, the human biometeorological assessment in a city offers a new approach to realise the local effects of weather and climate on daily life experiences at a level of a city, particularly in the low-latitude coastal tropics.

7 Conclusion

The preliminary analysis of the human biometeorological assessment of Dar es Salaam, a coastal tropic city, highlights the importance of thermal bioclimate research in different cities. The results indicate that afternoon hours are accompanied with relatively more discomfort conditions for human being; whereas the DJF season was observed to be the most uncomfortable season in a year. The JJA season was on the other hand observed to be a relative comfort season. Though, it can be observed that, people in the tropics have been acclimatised or adapted to warm temperatures, the assessment of discomfort is important since most discomfort indices involve other weather elements. In this study, PET was used compared to the earlier human thermal index of THI which is limited to the input parameters. It can therefore be considered that an improved human bioclimate assessment can be attained with universal thermal human index like PET which utilises all of the four meteorological elements that affects human thermal condition. Despite of using indices that base on the human thermal energy balance, comprehensive human bioclimate assessment can significantly be realised when combined with the use of high-resolution datasets preferably at hourly interval and longer period in order to reveal the climatology of the city in terms of thermal bioclimatic condition.

As the global population becomes urbanised and human activity concentrated in urban areas, settlement planning is a key aspect of sustainability especially in the fast growing cities in developing countries. Dar es Salaam being one of them, with its inclusion of environmental objectives in urban plans at all scales, provides also an opportunity for the incorporation of urban climate knowledge into the planning process on a routine basis. Bioclimatic information could also give a clear picture about the vulnerability of urban poor community to local climate change hence improving the means of securing adaptation strategies. Due to the observed high air humidity especially in the coastal cities in low latitudes, it then suggested and planned that further study on the bioclimate assessment particularly in Dar es Salaam should probably involve the thermal indices especially those strongly account for air humidity variables and the modification of thermal sensation through wind speed as provided by sea breezes. Modification of thermal indices' scales in line with the local adaption to thermal stress could also be taken into consideration.

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