ISSN 0354-8724 (hard copy) | ISSN 1820-7138 (online)

Potential Effects of Urbanization on Urban Thermal Comfort, a case study of Nairobi City, Kenya: A Review

Victor Ongoma[A,B*], **Pamela Kalondu Muange**[C], **Zablon Weku Shilenje**[C]
Received: May 31, 2015 | Revised: December 09, 2015 | Accepted: March 13, 2016
DOI: 10.18421/GP20.01-03

Abstract

This study reviews the effect of urbanization on human thermal comfort over Nairobi city in Kenya. Urbanization alters urban centre's land use and land cover, modifying the climate of the urban setting. The modification in climate affects human comfort and the environment at large. This study focuses on the recent studies conducted in Nairobi city and many other cities globally to examine modification of wind, temperature and humidity over Nairobi. There was observed reduction in wind speed and relative humidity over the city, posing threat to human and animal comfort and the environment at large. The city of Nairobi, just like other cities globally is observed to experience urban heat island (UHI). The observed increase in minimum temperature as compared to maximum temperature signifies overall warming. A combination of all these changes reduces human comfort. Borrowing lessons from developed cities, increasing the urban forest cover is thus suggested as one of the practical and effective measures that can help prevent further modification of weather and urban climates. The study recommends further research involving multi-sectoral urban stake holders, on forcing driving urban thermal comfort. In the short term, design and construction of appropriate structures can help minimize energy consumption and emissions, thus enhancing comfort.

Key words: thermal comfort, urban heat island, urbanization, Nairobi City

Introduction

Thermal comfort expresses the level of human satisfaction in a given environment. Thermal sensation of heat discomfort is felt under 'stable state', when the skin temperature is raised above the level corresponding to the state of comfort. The sensation helps human beings detect and respond to their environmental thermal conditions, and thus are able to live and work in almost any climate zone on earth despite the varying degrees of discomfort. Thermal comfort is closely linked to human health and is thus a key component in our daily operations (Evans, 1982). People who are exposed or work in uncomfortable environments are more likely to underperform or get involved in accidents because their ability to make decisions and / or perform manual tasks deteriorates (Shanu, 2010; Yilmaz et al., 2007). Thermal comfort, both indoor and outdoor has been widely studied, and continues to gain interest owing to the changing living environments.

Weather parameters: air temperature, humidity and wind speed and direction significantly influence the physiological sensation of human comfort. Human thermal comfort or discomfort may thus be determined by using a varying number of both theoretical and empirical indices that consider a number of parameters such as air temperature, wind, humidity, and clothing (Unger, 1999).

[A] College of Atmospheric Sciences, Nanjing University of Information Science and Technology, Nanjing 210044, P.R. China
[B] Department of Meteorology, South Eastern Kenya University, P.O. Box 170-90200, Kitui-Kenya
[C] Kenya Meteorological Department, P.O. Box 30259-00100, Nairobi-Kenya
* Corresponding author: Victor Ongoma, e-mail: victor.ongoma@gmail.com

The art of determining thermal comfort conditions started long time ago; it is one of the key issues in biometeorology. Today, approximately fifty different human thermal comfort indices exist. These indices have been developed on the basis of the physiological feeling of a significant number of people, among them, the widely used indices are: Thom (1959) - Discomfort Index (DI), Givoni (1963) - Standard Equivalent Temperature (SET), Fanger (1970) - Predicted Mean Vote (PMV) and Höppe (1999) - Physiological Equivalent Temperature (PET). The quantification of the comfort has advanced recently following the development of Universal Thermal Climate Index (UTCI) by the European COST Action 730 (Cooperation in Science and Technical Development) project (McGregor, 2012). The development was initiated since the previous methods exhibited significant shortcomings (Jendritzky et al., 2012, 2007).

Fiala et al. (2012) came up with a UTCI known as UTCI-Fiala mathematical model of human temperature regulation. The model predicts human temperature and regulatory responses under various outdoor weather conditions. The approach is hailed to form the basis of the new UTCI. The index utilizes the concept of equivalent human physiological responses to combinations of air temperature, radiation, wind and humidity. Havenith et al. (2012) developed UTCI-clothing model that considers the typical dressing behaviour in different temperatures. The output of the model defines in detail the effective clothing insulation and vapour resistance for each of the thermo-physiological model's body parts in varying climatic conditions. The model together with the UTCI-Fiala model defines the heat transfer characteristics between the human skin and the environment. However, according to Bröde et al. (2012) in consideration of how the clothing model was developed, the clothing behaviour adopted gives a good representation of the European and North American urban populations and therefore, its output requires further validation, although initial results may be applicable to other urban centres globally.

In assessment of the performance of the UTCI, Blazejczyk et al. (2012) carried out a comparison of UTCI to selected thermal indices. The study focused on three groups of data, namely: global data-set, synoptic datasets from Europe, and local scale data from special measurement campaigns of COST Action 730. The performance of other indices was limited to specific meteorological conditions, as compared to the UTCI that gives a better representation of thermal comfort across different climates, weather, and locations. In addition, just like the human body, the UTCI is highly sensitive to changes in ambient stimuli: temperature, solar radiation, wind and humidity as compared to other indices. The UTCI has been successfully applied in thermal comfort studies and is becoming popular globally (Park et al., 2014; Błazejczyk et al., 2013).

Urban growth is quantified by the growth of population and industries. Consequently, this growth leads to increase in socio-economic activities leading to changes in land use and decrease in land cover. Although the activities are aimed at betterment of human life, in some cases, they can pose challenges, hindering growth if not well planned and executed (Moonen et al., 2012). According to United Nations (2014), the growth in population and industrialization today is a global phenomenon with 54 percent of the world's population living in urban areas in 2014 (Figure 1). Although Africa and Asia are the least urbanized today, they are currently urbanizing faster than other regions. On a regional scale, Kenya is experiencing rapid urbanization growth just like many other developing countries in Africa (UN Habitat, 2008; United Nations, 2001). The construction of buildings,

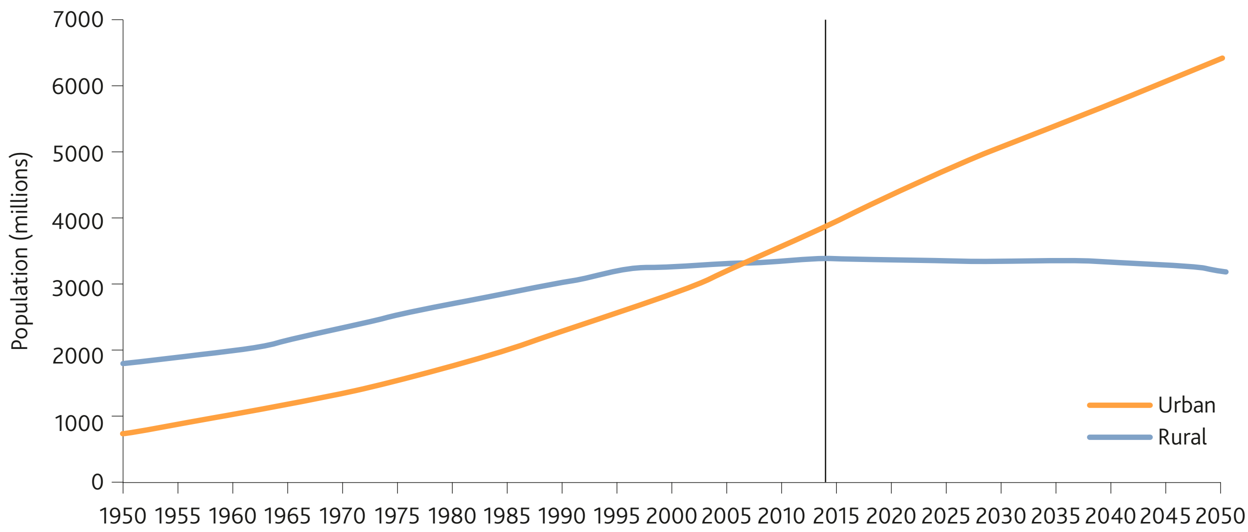

Figure 1. Urban and rural population of the world, 1950–2050 *(Source: UN, 2014)*

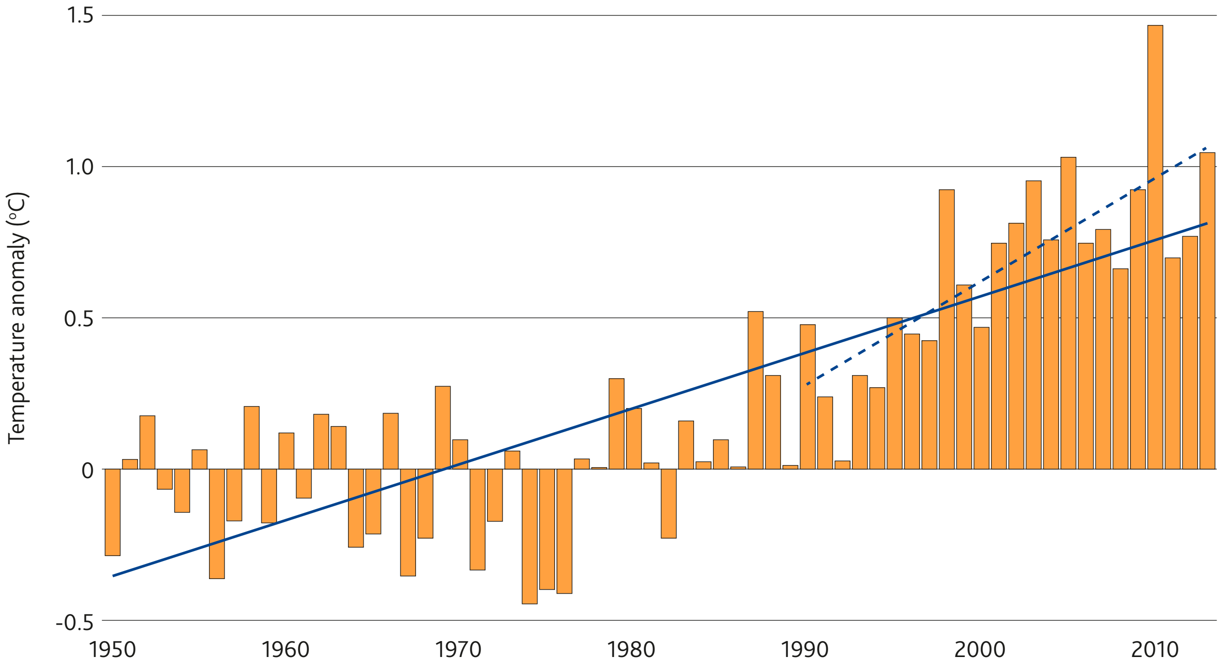

Figure 2. Temperature anomaly over Africa from 1950 to 2013 with respect to 1961–1990; gridded data based on station observations *(Source: WMO, 2015)*

roads and increase in human and vehicular traffic creates its own micro-climates (Unger, 1999; Oke, 1982; Adebayo, 1991). The changes in land use and land cover alter the exchange of energy, momentum, moisture, and other trace gases within vegetation-soil-atmosphere system, subsequently affecting the global and regional climate (Foley et al., 2005).

The potential for steadily increasing temperatures and air pollution coupled with a projected population increase from 54 percent today to about 70 percent by 2050 (UNFPA, 2007; IPCC, 2007), greatly increase the need for urban inhabitants, public health sector, planners and decision makers to devise effective strategies of managing microclimates in rapidly growing urban areas. Global studies have reported increasing temperatures especially in the last three decades, mostly attributed to climate change (IPCC, 2007; 2014). For instance, according to the recent World Meteorological Organization (WMO) report on climate of Africa (WMO, 2015), recent years have reported the largest positive temperature anomalies (Figure 2). However, despite the existence of information on the changing climate and the ongoing urbanization that greatly affect human comfort, there is limited information on measurement and monitoring of thermal comfort over most cities in developing countries especially in Africa, the city of Nairobi and Kenya at large (Ongoma and Muthama, 2014).

Urban growth along with the increased built infrastructure, determines the climate in cities resulting in distinct urban climatic condition (Blake et al., 2011). Previous studies show that the effects of urbanization on weather and climate are noticeable even in population setting of as small as 1000 and the intensity of urban heat island is linearly correlated with the logarithms of the population (Karl et al., 1988). The study affirmed that population is an indicator of urbanization; the results showed that a population of as a few people as 10,000 has effect on urban climate.

Generally, limited urban climate studies have been carried out in developing countries. Most studies that have been conducted in the countries focus on urban and non-urban temperature differences; this is partly explained by limited data. Studies on the impact of urban climate on human comfort are very few. Although Ongoma and Muthama (2014) reported that the larger county of Nairobi does not experience heat stress throughout the year, the study was carried out over a short period of time, and in the ongoing socio-economic development and global warming, there is need of continued study and monitoring of thermal comfort in the city. The aim of this study is to assess the potential effects of urbanization on human thermal comfort over Nairobi city. The study specifically reviews the influence of urbanization on wind, air temperature and humidity over Nairobi city and assesses the possible effect of modification of the three weather parameters on human thermal comfort. This study will serve as a wakeup call to urban planners and structural designers to enhance human comfort in the city of Nairobi by designing adequate mitigation strategies to climate related risks. Generally, basic understanding of how climate affects human beings and the environment at large is a key aspect in planning, and helps in devising suitable avenues, measures, technologies, and policies to improve the adaptive capacity to climate (Jendritzky and Dear, 2009).

The study employed review of relevant recently peer reviewed publications both at global and local scale studies. The key studies considered are: Argüeso et al., 2015; WMO, 2015; Demuzere et al., 2014; Park et al., 2014; Schats and Kucharik, 2014; Ongoma et al., 2013a, b; Ongoma and Muthama, 2014; Yang et al., 2013; Li et al., 2013; Fischer et al., 2012; Fiala et al., 2012; Kolokotroni et al., 2012; Brandsma and Wolters, 2012; Ryu and Baik, 2012; Hwang et al., 2011; Robaa, 2003, 2011; Luber and McGeehin 2008; Adebayo, 1991; Zhou et al., 2004; Oke, 1973; Toy and Yilmaz, 2010; Liu et al., 2009; Chen et al., 2006; Makokha and Shisanya, 2010.

The study used monthly rainfall data; 1951-2010, from Climate Research Unit (CRU) to show annual temperature cycle and inter-annual temperature variability over Nairobi City. The CRU temperature data, version TS3.22 is provided by a division of the University of East Anglia. The data is gridded at 0.5° x 0.5° resolution, running from 1901 to 2013. The CRU data is discussed in detail by Harris et al. (2014). The CRU Time Series v3.22 (TS3.22) dataset is described at length by the University of East Anglia Climatic Research Unit et al. (2014).

Area of Study

Nairobi, Kenya's capital city is located within latitude 1° 9'S, 1° 28'S and longitude 36° 4'E, 37° 10'E (Figure 3). The city covers an area of approximately 684 km2, with a population of 3.1 million people (KNBS, 2010). The city was established around 1899 by the colonial government as a railway terminus for the Kenya-Uganda railway (Obudho, 1999). The city has been growing since then. Mundia and Aniya (2006) noted significant increase in urban built-up areas linked to economic growth and population expansion.

Nairobi experiences bimodal rainfall regime with 'long rain' season in March-May (MAM) and 'short rains' in October-December (OND) (Okoola, 1996; 1999; Yang et al., 2015). The predominant winds over the city are easterlies; they are associated with precipitation occasioned by moisture inflow into the country from the Indian Ocean (Opijah et al., 2007; Ongoma et al., 2013a). The highest temperature is reported in the MAM season, followed by OND (Figure 4), which coincides with the main rainfall seasons of the city. The temperature, just as rainfall over the city is mainly influenced by the north-south movement of the ITCZ (Okoola, 1996). The June - August (JJA) is the coldest season, linked to cold air advection from the southern hemisphere that experiences winter during the time.

Results and discussion

Weather parameters such as air temperature, air humidity, wind speed and solar radiation affect evaluations of thermal comfort e.g. thermal perception and satisfaction. Wind speed and temperature are the important environmental factors contributing to the comfort.

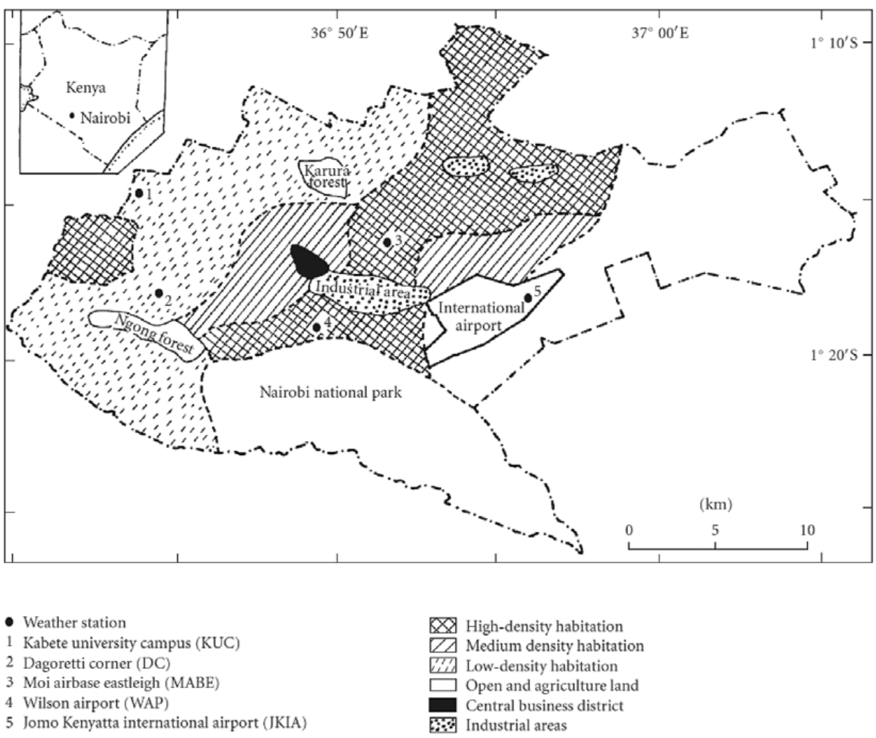

Figure 3. Land use and geographical location of weather stations in Nairobi
(Source: Makokha and Shisanya, 2010)

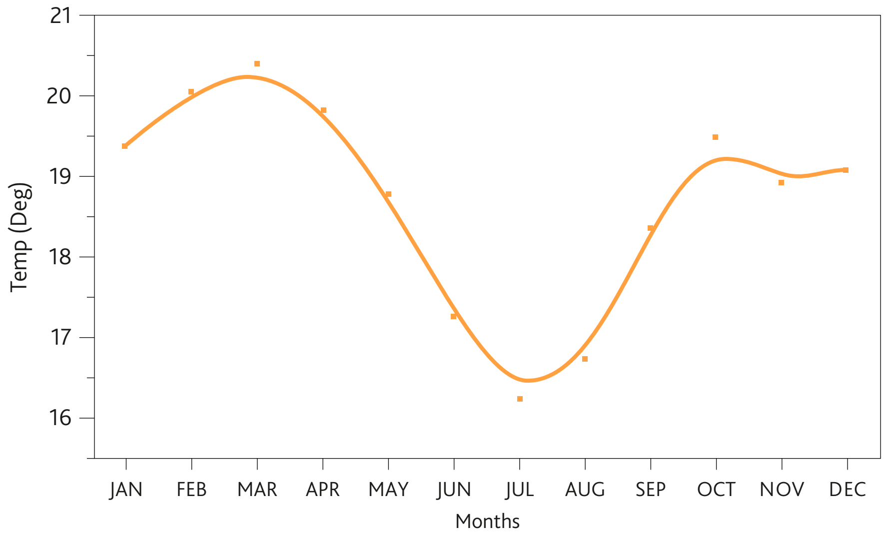

Figure 4. Annual temperature cycle over Nairobi city based on CRU data, 1951–2010

Urbanization

Urbanization in Nairobi city is evidenced through population growth and land surface reflectivity changes. Population growth in Nairobi city is partly explained by net migration into the city (KNBS, 2010) while the land albedo is observed to decrease over the city with time (Ongoma, et al., 2013a). The reflectivity of the city ranges between 0.12 and 0.15 (Ongoma, 2012). Muthoka and Ndegwa (2014) studied the dynamism of land use changes on surface temperature over Kenya, focusing on Nairobi city. The study showed a reduction in vegetation cover to bare land or built-up; an evidence of a growing city.

Njoroge et al. (2011) assessed the landscape change and occurrence at watershed level in city of Nairobi. The study observed significant changes in the spatial configuration of the landscape of Nairobi city between 1976 and the year 2000. According to the study, land use related to human activities such as built areas increased to the detriment of wetland and vegetated areas, signifying the city's growth.

According to studies (e.g. Zhang et al., 1995; Schats and Kucharik, 2014), land surface reflectivity is one of the most important parameters that characterize the earth's radioactive regime and its impact on biospheric and climatic processes. Oke (1973) measured urban albedo and found it to range from 0.08 to 0.20 in United States' cities. The study attributed the observation to the complicated urban surface geometries that causes multiple reflections and trapping of radiation with the canyon spaces.

Thermal Comfort

A research conducted in hot and humid conditions indicated that few people visit squares or other public spaces when the thermal index is high (Lin, 2009). In Egypt, Robaa (2011) investigated the effect of urbanization and industrialization processes on outdoor thermal human comfort in greater Cairo region. The study noted that the processes are responsible for increase of human hot uncomfortable feeling, which hinders human activities in the urban area, while the rural conditions lead to optimum weather comfort for further and more human activities. A study by Toy and Yilmaz (2010) looked at the extent of the effects of a medium-sized, unindustrialized and well planned city in Turkey on human thermal comfort conditions. The study achieved this by comparing the results of thermal comfort calculations, by means of meteorological data from 1999 to 2008 taken from non-urban and urban areas and thermohygrometric index (THI) and predicted mean vote (PMV) indices. From the evaluation, it was found that both THI and PMV values are higher in urban area than those in rural area nearly all year round. However, the effect of the city on human thermal comfort was found to be statistically not significant.

Park et al. (2014) investigated human thermal sensation on human bioclimatic maps in summer, 2009 using the UTCI in Nanaimo, BC, Canada and Changwon, Republic of Korea. According to the study, the greatest heat stress is experienced mid-afternoon. Generally, open sunny areas had moderate to strong heat stress, while shady areas had no thermal stress to moderate heat stress. This explains the direct link between temperature and thermal comfort; generally, high temperatures are associated with high discomfort as compared to the experience in lower temperature of a similar setting. The study further noted that narrow streets had lower UTCI's than open spaces in both areas. The width of the streets can be linked to wind speed, where narrow streets are associated with wind tunneling effect. The effect reduces air temperature at a point of passage, consequently increasing thermal comfort level.

A study of seasonal effects of urban street shading on long-term outdoor thermal comfort in central Taiwan by Hwang et al. (2011), using RayMan model, showed that slightly shaded zones typically have highly frequent hot conditions during summer, particularly at noon. The same study noted that highly shaded areas generally have a low physiologically equivalent temperature (PET) during winter. The study recommended shading as one of the best options in improving thermal environment for urban streets.

Indoor thermal comfort in urban areas has gained a lot of interest since people spend most hours of the day indoors; yet, it happens that most houses are not well ventilated to enhance comfort. The indoor thermal comfort is very serious as it is not only influenced by the housing and its activities, but also by the prevailing outdoor environmental condition. Effective planning of urban structures can only be achieved with the knowledge of the prevailing and anticipated climate information (Jendritzky and Dear, 2009). In Nairobi and Kenya at large, there are no existing laws governing walls in buildings in the effort to enhance comfort (Kariuki et al., 2015). The ongoing unplanned constructions, especially in informal settlements, in the awake of global warming and UHI enhancement, will reduce the thermal comfort of city residents in the near future. Ogoli (2003) developed a formula for predicting indoor maximum temperatures for closed high mass buildings at equatorial high altitudes. The study assessed the effect of thermal mass in lowering the maximum indoor daytime temperatures. The findings showed that the low mass test chambers closely followed outdoor conditions; did not offer any significant thermal storage.

Ongoma and Muthama (2014) reviewed and assessed the applicability of the heat stress indices in Kenyan weather forecasts. The study tested the applicability of Discomfort Index (DI) in Kenyan daily weather forecasts using observed station and forecast dry bulb and wet bulb temperature data from Consortium for Small-Scale Modelling (COSMO) model used by Kenya Meteorological Department (KMD). According to the study, the COSMO model gives a relatively good prediction of DI in Kenya. The study that only considered datasets spanning for one year observed that in the highlands east and west of Rift Valley and Nairobi counties do not experience heat stress throughout the year. However, noting the limitation of the data, the study called for further research on the same, utilizing longer data sets.

Temperature

Transformation of natural surfaces into urbanized ones and anthropogenic activities mainly alter the radiation balance causing albedo differences (Ryu and Baik, 2012; Li et al., 2013). The result of these combined effects and additional heat emission of anthropogenic activities, urban environment is generally found to be warmer than its natural/rural counterparts with a varying degree, a condition termed as Urban Heat Island (UHI) (Stewart and Oke 2012; Toy and Yilmaz, 2010; Oke 1973, 1982; Li et al., 2013; Landsberg, 1981). The study by Oke (1982) linked the occurrence of UHI to a number of factors among them: increase in storage capacity of sensible heat in the construction materials, anthropogenic heat released from vehicles, industries and domestic heating, decreased long-wave radiative heat losses as a result of reduced sky-view factors, a reduction in potential for evapotranspiration and reduction of wind speed which limits convective heat removal from the city.

In as much as the contribution of UHI to global climate change may not be significant, the opposite is concern, and worth of monitoring. Currently, studies have clearly shown that the earth is warming (IPCC, 2007). The study attributes the warming to the emission of greenhouse gases (GHG). GHG emission is expected to continue, projecting continued increase in global warming. The challenges associated with the global warming include increases in frequency and intensity of hot extremes, heat waves and heavy precipitation. According to Voogt (2002), global climate change will increase thermal challenge in urban areas by intensifying UHI impacts. According to a recent study by Argüeso et al. (2015), the joint contribution of urban expansion and climate change on heat stress over the Sydney region will lead to increased risk of heat-stress conditions, with substantially more frequent adverse conditions in urban areas.

Researchers have approached and examined UHI in different ways. Temporal and spatial characteristics of UHI have been examined using observations at fixed points; representing non-urban and urban settings (e.g. Schats and Kucharik, 2014) and in some cases, measurements are carried out on mobile platforms (e.g. Brandsma and Wolters, 2012). The extent of urban warming is highly variable over both time and space, on average, urban temperatures may be 1 - 3°C warmer, under appropriate meteorological conditions (Oke, 1981). The UHI intensity is generally higher at night as compared to daytime (Schats and Kucharik, 2014; Yang et al., 2013; Brandsma and Wolters, 2012).

In Melbourne, Australia, Morris (2005) investigated the occurrence of UHI in Australian Central Business District (CBD) and the Industrial Suburbs (IS). The study found that UHI was most pronounced when the wind speed in the CBD and IS was less than 3 m/s. It was further ascertained that during clear sky con-

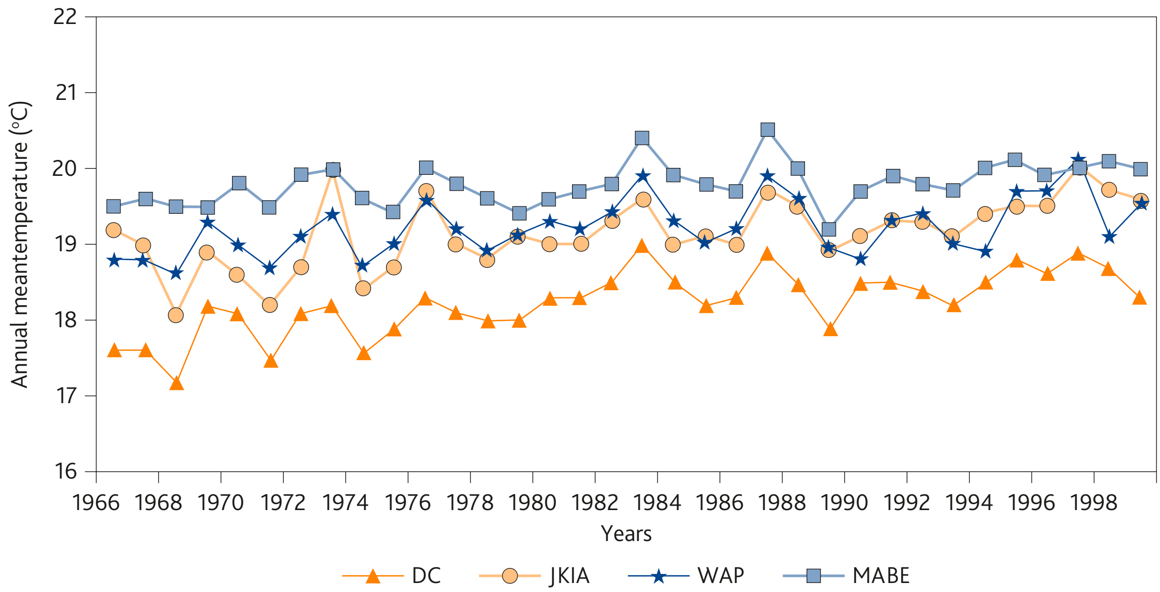

Figure 5. Mean Annual Temperature Time Series over Nairobi City
(MABE - Moi Air Base Eastleigh, WAP - Wilson Airport, JKIA - Jomo Kenyatta International Airport, DC - Dagoretti Corner)
(Source: Makokha and Shisanya, 2010)

ditions and wind speeds less than 1.5 m/s, the heat island was as high as 10°C around midnight. As expected to the contrary, during very windy evenings, the heat retained by the urban area was dispersed more easily which resulted in a smaller difference between the CBD and the outer suburbs.

A study by King'uyu et al. (2000) pointed out warming over the larger east Africa. According to the study, the warming was characterized by general nighttime warming; reduction in diurnal temperature range. A perfect locality that exhibited this temperature pattern is Dagoretti Corner in Nairobi. The same observations were made in a more recent study by King'uyu et al. (2011). The latter attributed the more prominent nighttime warming as compared to day time warming over Nairobi to urbanization.

Ongoma et al., (2012, 2013a) and Makokha and Shisanya (2010) observed increase in both minimum and maximum temperature of the city of Nairobi (Figure 5). An analysis of mean annual temperature over the city using Climate Research Unit (CRU) data, 1951-2010, shows increasing temperature trend since 1970s to date (Figure 6). The highest change in temperature has been observed in the recent past, between 1990s and 2010s. A summary of the mean decadal temperatures is presented in Table 1. However, the increasing trend cannot be entirely attributed to urbanization since global warming is also a factor behind atmos-

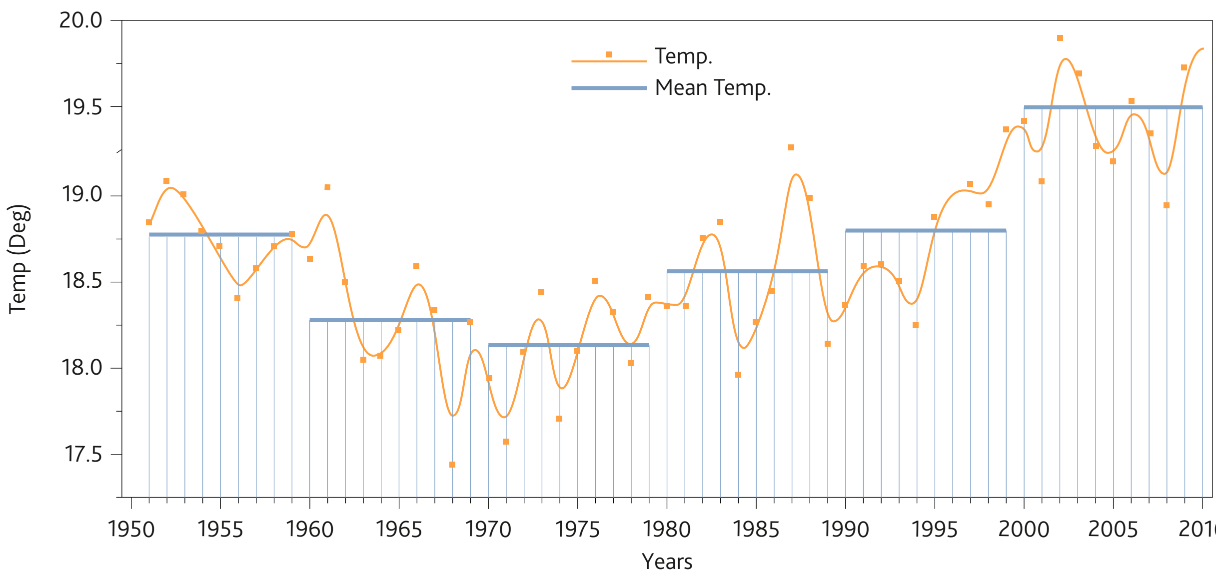

Figure 6. Temperature variability over Nairobi city based on CRU data, 1951 -2010 (Orange – Interannual; Blue – Decadal)

Table 1. Decadal temperature over Nairobi city, based on CRU data, 1951–2010

Years	1950s	1960s	1970s	1980s	1990s	2000s
Temp. (°C)	18.8	18.3	18.1	18.6	18.8	19.5

pheric warming globally. There is need for high resolution datasets, and advanced data analysis techniques to distinguish the contribution of urbanization from the global warming on the observed temperature.

Makokha and Shisanya (2010) examined the long-term urban modification of mean annual conditions of near surface temperature in Nairobi City. According to the study the change of temperature over the thirty-four years study period is higher for minimum temperature than maximum temperature. The warming trends were observed to be more significant at the urban stations than is the case at the sub-urban stations, the temperatures were observed to increase with increase in proximity to the CBD. This is an indication of the spread of urbanization from the built-up CBD to the suburbs. According to Figure 5, temperature recorded in the city increases from Jomo Kenyatta International Airport (JKIA), to Wilson Airport (WAP) and Moi Air Base Eastleigh (MABE), in the same order in which their proximity to the CBD increases. Although Dagoretti Corner (DC) is close to the CBD as compared to JKIA, its temperature is low than what is recorded at JKIA. This observation could be attributed to the location of DC on the western side of the CBD where the temperature is generally lower than the eastern side (Ongoma, 2012). The observed significant warming trends in minimum temperature, which are likely to reach higher proportions in future, pose serious challenges on climate and urban planning of the city.

These studies are in agreement with Chen et al. (2006); a study carried out to investigate UHI intensity during the period of 1961-2000 in Wuhan, China by analyzing annual mean, mean minimum and maximum temperature anomalies from a set of one non-urban station and four urban stations. The study found out that significant warming of mean minimum temperature and annual mean temperatures occurred at all stations. However, it was noted that warming was being significantly larger at the urban stations.

A study carried out by Okoola (1980) investigating UHI using 9-year minimum and maximum temperature observations over the city of Nairobi revealed that the maximum UHI intensity lay to the north east of the main city centre. The highest mean monthly urban - non-urban contrast was noted to occur during the months of January and February. Ongoma (2012) observed similar case where the generally the eastern part of the city exhibited a positive temperature anomaly as compared to the western side that had a negative anomaly (Figure 7).

The occurrence of UHI in cities is likely to aggravate the problem because longer-term effects of global climate change (Fischer et al., 2012; Luber and McGeehin, 2008). This will lead to further increases in temperatures in an urban microclimate with negative implications for energy and water consumption (Kolokotroni et al., 2012), human health and discomfort, local ecosystems, and as increasing chances for the formation of some atmospheric pollutants (Arnfield, 2003; Akbari, 2005).

Wind

Urban wind is greatly influenced by obstacles such as structures and orientation. Wind speed and direction

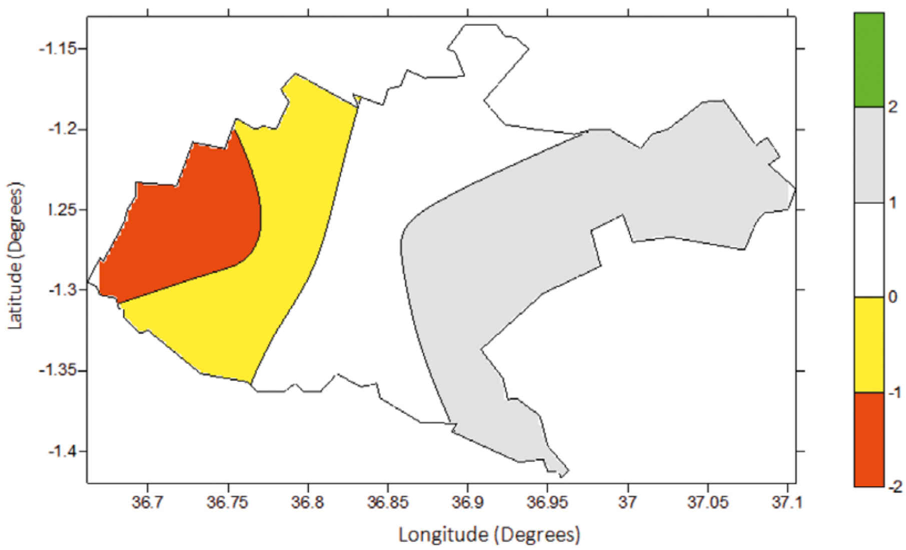

Figure 7. Spatial distribution of Maximum Temperature Deviation from the mean distribution over Nairobi, 1991 -2010 *(Source: Ongoma, 2012)*

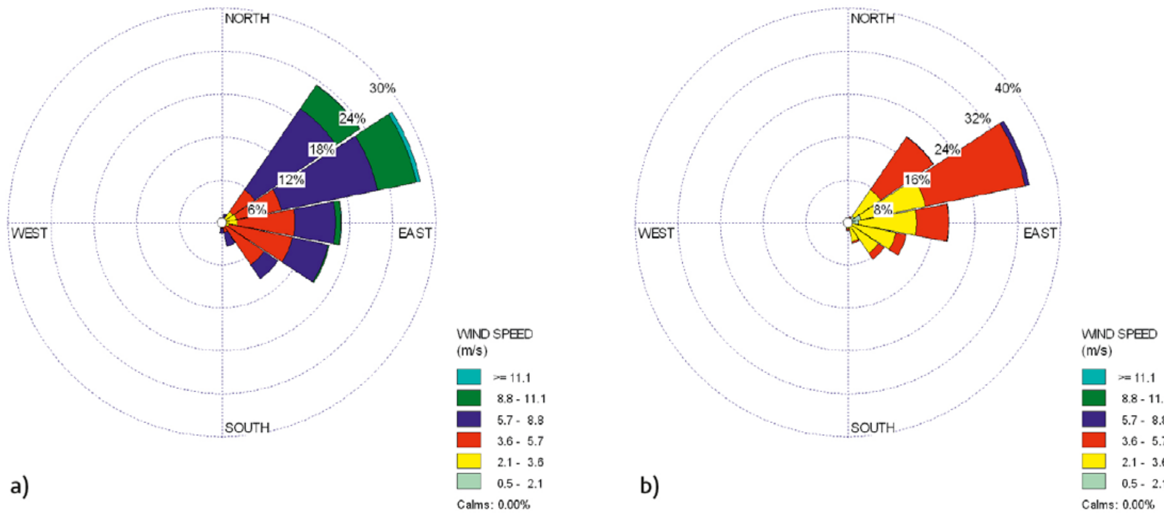

Figure 8. Nairobi City wind roses for (a) 1991 - 2000 (b) 2001 -2010
(Source: Ongoma et al., 2013b)

greatly affects thermal comfort (Mochida and Lun, 2008). Wind affects dispersion of pollutants in the city and distribution of heat which affects human comfort. The dominant winds over the city of Nairobi are easterlies (Opijah et al., 2007; Ongoma et al., 2013). A study carried out over the city by Ongoma et al. (2013b) observed a decrease in wind speed with time although the directions remain constant (Figure 8).

The reduction in wind speeds with the growth of the city is explained by change in surface roughness as well as enhanced temperatures that reduce pressure over the city forming a centre of low level convergence. Altered surfaces of urban areas can also cause windless environments where tall and densely constructed buildings may serve as obstacles to wind.

On the other hand, high-rise city structures with open walk and driveways can enhance wind tunneling effect, which is associated with strong wind that cause discomfort in the outdoor. The strong wind not only causes discomfort discouraging people from visiting the city streets (Wise, 1970), and also increases cases of property destruction which threaten people's security.

Humidity

Humidity is an important factor in the determination of human comfort extent. Imbalances in the characteristics of urban atmosphere caused by the factors such as dense construction and land use variations can generally cause drier urban atmosphere depending on time of the day and year (Liu et al., 2009). Generally most urbanized cities show drier urban centres in the afternoon and early evening, but moister at night (Schats and Kucharik, 2014; Liu et al., 2009; Robaa, 2003). A study carried out over the city of Nairobi in 2010 by Ongoma et al., (2010) reported a general decrease in humidity of the city. This is in agreement with Unkasevic et al. (2001), in a study that compared the urban against non-urban water vapor pressure and relative humidity (RH) in Belgrade and found out that urban area is drier than others in the afternoon throughout the year. Similarly, Fortuniak et al. (2006) analyzed data from two automatic stations in Poland (one non-urban and one urban) for a period of 1997-2007, the study found out that relative humidity (RH) is lower in town, sometimes by more than 40%.

A case study of day-time effects of urbanization on RH and vapour pressure in a tropical city, Ibadan - Nigeria observed that urbanization has a significant effect on both RH and vapour pressure (Adebayo, 1991). The changes were noted in the afternoon and during dry season. Although the two parameters were affected by urbanization in the same manner, the effect was greater on RH as compared to vapour pressure.

Conclusion

The ongoing increase in urbanization, coupled with global warming generally modify climate creating microclimates in different cities. Studies carried out in urban centres globally acknowledge that UHI is a growing threat to human thermal comfort in the cities.

This study has revealed the influence of urbanization on urban climate. The increases in both maximum and minimum temperature affect human comfort. Humidity is observed to generally decrease over the city of Nairobi. It is also noted that wind speed is decreasing over the city; wind speed and direction affect dispersion of pollutants and distribution of heat which affects human comfort in the city. The reduction in wind speed over the city reduces the thermal comfort of its inhabitants. The findings of this work are thus important for multi-sectoral use in designing Kenyan cities.

Despite of the rich knowledge on urban climate, borrowing lessons from the highly developed cities today, unfortunately, there is still a need to bridge the gap between the science and its practical application. Since the thermal discomfort in no serious problem today over Nairobi and likely over other Kenya cities, there is need and room for formulating and effecting long term urban development standards, by providing practical tools for urban planning purposes.

This study thus recommends use of practical approaches such as increasing the urban forest cover and a proper planning of the city to help prevent further modification of weather and climate through inter-disciplinary approach. For instance, in urban environments, open green spaces not only contribute to urban image and aesthetics, but also improve urban climate, thus these spaces may be considered as a favourable factor on decreasing the urban - non-urban climatic differences (Demuzere et al., 2014; Pauleit et al., 2011). The study calls for continuous research that focuses on urban thermal comfort: indoor and outdoor, especially in urban structures. Such research will require high resolution and relatively long data sets, and advanced data analysis techniques to achieve quality results.

Acknowledgement

The authors acknowledge their respective institutions for continuous motivation and providing an enabling environment that fosters research. Special appreciation goes to University of East Anglia Climatic Research Unit for providing the temperature data used in the city. A lot of thanks go to the two anonymous reviewers who provided additional information to improve the quality of this work.

References

Abedayo Y.R., 1991. Day-time Effects of Urbanization on Relative Humidity and Vapour Pressure in a Tropical City. *Theoretical and Applied Climatology*, 43, 17-30. doi:10.1007/BF00865039

Akbari H., 2005. Energy Saving Potentials and Air Quality Benefits of Urban Heat Island Mitigation. LBNL-58285. Lawrence Berkeley National Laboratory, Berkeley, CA.

Argüeso D., Evans J.P., Pitman A.J., Di Luca A., 2015. Effects of city expansion on heat stress under climate change conditions. *PLoS ONE*, 10, e0117066. http://doi.org/10.1371/journal.pone.0117066

Arnfield J.A., 2003. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal Climatology*, 23, 1-26. DOI: 10.1002/joc.859

Blake R., Grimm A., Ichinose T., Horton R., Gaffin S., Jiong S., Bader D., Cecil L.D., 2011. Urban climate: Processes, trends, and projections. Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network, [Rosenzweig C., Solecki WD, Hammer SA, Mehrotra S, (eds.)], Cambridge University Press, Cambridge, UK, 43-81.

Blazejczyk K., Epstein Y., Jendritzky G., Staiger H., Tinz B., 2012. Comparison of UTCI to selected thermal indices. *International Journal of Biometeorology*, 56, 515–535. http://doi.org/10.1007/s00484-011-0453-2

Błazejczyk K., Jendritzky G., Bröde P., Fiala D., Havenith G., Epstein Y., Psikuta A., Kampmann B., 2013. An introduction to the Universal thermal climate index (UTCI). *Geographia Polonica*, 86, 5–10. http://doi.org/10.7163/GPol.2013.1

Brandsma T., Wolters D., 2012. Measurement and Statistical Modeling of the Urban Heat Island of the City of Utrecht (the Netherlands). *Journal of Applied Meteorology and Climatology,* 51, 1046-1060. DOI: 10.1175/JAMC-D-11-0206.1

Bröde P., Krüger E.L., Rossi F.A., Fiala D., 2012. Predicting urban outdoor thermal comfort by the Universal Thermal Climate Index UTCI-a case study in Southern Brazil. *International Journal of Biometeorology,* 56, 471–480. http://doi.org/10.1007/s00484-011-0452-3

Demuzere M., Orru K., Heidrich O., Olazabal E., Geneletti D., Orru H., Bhave A.G., Mittal N., Feliu E., Faehnle M., 2014. Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *Journal of Environmental Management,* 146, 107-115. doi:10.1016/j.jenvman.2014.07.025

Epstein Y., Moran D.S., 2006. Thermal comfort and the heat stress indices. *Industrial Health*, 44, 388-398.

Evans G.W., 1982. Environmental Stress. Cambridge University Press.

Fanger P.O., 1970. *Thermal comfort.* Copenhagen, Danish Technical Press, 244 pp.

Fischer E.M., Oleson K.W., Lawrence D.M., 2012. Contrasting urban and rural heat stress responses to climate change. *Geophysical Research Letters,* 39, L03705, doi:10.1029/2011GL050576.

Foley J.A., DeFries R., Asner G.P., Barford C., Bonan G., Carpenter S.R., Chapin F.S., Coe M. T., Daily G.C., Gibbs H. K., Helkowski J.H., Holloway T., Howard E.A., Kucharik C.J., Monfreda C., Patz J.A., Prentice I.C., Ramankutty N., Snyder P.K., 2005. Global consequences of land use: Review. *Science*, 309, 570-574.

Fortuniak K., Klysik K., Wibig J., 2006. Urban-rural contrasts of meteorological parameters in Lódź. *Theoretical and Applied Climatology*, 84, 91-101. DOI: 10.1007/s00704-005-0147-y

Givoni B., 1963. *Man climate and architecture*. Amsterdam: Elsevier Press, 247 pp.

Harris I., Jones P.D., Osborn T.J., Lister D.H., 2014. Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset. *International Journal of Climatology*, 34,623-642. doi:10.1002/joc.3711

Havenith G., Fiala D., Blazejczyk K., Richards M., Bröde P., Holmér I., Rintamaki H., Benshabat Y., Jendritzky G., 2012. The UTCI-clothing model. *International Journal of Biometeorology,* 56, 461–470. http://doi.org/10.1007/s00484-011-0451-4

Höppe P., 1999. The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology*, 43, 71-75.

Hwang R.-L., Lin T.-P., Matzarakis A., 2011. Seasonal effects of urban street shading on long-term outdoor thermal comfort. *Building and Environment,* 46, 863–870. http://doi.org/10.1016/j.buildenv.2010.10.017

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., Miller H.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri R.K., Meyer L.A. (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Jendritzky G., de Dear R., Havenith G., 2012. UTCI—Why another thermal index? *International Journal of Biometeorology,* 56:421-428. DOI 10.1007/s00484-011-0513-7

Jendritzky G., Havenith G., Weihs P., Batchvarova E., de Dear R., 2007. The Universal Thermal Climate Index UTCI Goal and State of COST Action 730. *Environmental Ergonomics XII2*, 509–512.

Jendritzky G., de Dear R., 2009. Adaptation and Thermal Environment. In Ebi K.L., Burton I., McGregor G.R. (eds), Biometeorology for Adaptation to Climate Variability and Change, *Biometerology Series*, 1, 9–32. http://doi.org/10.1007/978-1-4020-8921-3_2

Kariuki R.N., Mugwima B.N., Kaluli J.W., 2015. Determination of the Thermo-physical Properties of Walling Materials for Thermal Comfort in the Sub-Tropic Highland Climate, Kenya. *Proceedings of the Sustainable Research and Innovation (SRI) Conference, 6 - 8 May, 2015*, Nairobi, Kenya

Karl T.R., Diaz H.F., Kukia G., 1988. Urbanization; Its detection and effects in the United States climate record. *Journal of Climate,* 1, 1099-1123. doi: http://dx.doi.org/10.1175/1520-0442(1988)001<1099:UIDAEI>2.0.CO;2

King'uyu S.M., Ogallo L.A., Anyamba E.K., 2000. Recent Trends of Minimum and Maximum Surface Temperatures over Eastern Africa. *Journal of Climate*, 13, 2876–2886. doi: http://dx.doi.org/10.1175/1520-0442(2000)013<2876:RTOMAM>2.0.CO;2

King'uyu S.M., Kilavi M., Omeny P., Muigai E., Njogu A.K., 2011. Climate change indices for Kenya. *Journal of Meteorology and Related Sciences*, 5,49-55.

Kolokotroni M., Ren X., Davies M., Mavrogianni A., 2012. London's urban heat island: Impact on current and future energy consumption in office buildings. *Energy and Buildings,* 47, 302-311. doi:10.1016/j.enbuild.2011.12.019.

Landsberg H.E., 1981. The Urban Climate. New York, Academic Press, 84-122.

Li Y., Zhu L., Zhao X., Li S., Yan Y., 2013. Urbanization Impact on Temperature Change in China with Emphasis on Land Cover Change and Human Activity. *Journal of Climate,* 26, 8765-8780. DOI: 10.1175/JCLI-D-12-00698.1

Lin T.P., Matzarakis A., Hwang R.L., Huang Y.C., 2010. Effect of pavements albedo on long-term outdoor thermal comfort. In Proceedings of the 7th Conference on Biometeorology. Ber Meteorol Inst Univ Freiburg, 20, 498-504.

Liu W., You H., Dou J., 2009. Urban-rural humidity and temperature differences in the Beijing area. *Theoretical Applied Climatology*, 96, 201-207. DOI: 10.1007/s00704-008-0024-6

Luber G., McGeehan M., 2008. Climate change and extreme heat events. *American Journal Preventive Medicine,* 35, 429-435, doi:10.1016/j.amepre.2008.08.021.

Makokha G.L., Shisanya C.A., 2010. Trends in Mean annual minimum and Maximum near Surface Temperature in Nairobi City, Kenya. *Advances in Meteorology*, 2010. doi:10.1155/2010/676041.

McGregor G.R., 2012. Special issue: Universal Thermal Climate Index (UTCI). *International Journal of Biometeorology*, 56:419. DOI 10.1007/s00484-012-0546-6

Mochida A., Lun I.Y.F., 2008. Prediction of wind environment and thermal comfort at pedestrian level in urban area. *Journal of Wind Engineering and Industrial Aerodynamics*, 96, 1498–1527

Moonen P., Defraeye T., Dorer V., Blocken B., Carmeliet J., 2012. Urban Physics: Effect of the micro-climate on comfort, health and energy demand. *Frontiers of Architectural Research,* 1, 197–228. http://doi.org/10.1016/j.foar.2012.05.002

Morris C.J.G., 2005. Urban Heat Islands and Climate Change – Melbourne Australia. School of earth Sciences, University of Melbourne, Victoria, Australia. On line at http://www.earthsci.unimelb.edu.au/ (Accessed on 25/06/2014).

Mundia C.N., Aniya M., 2006. Dynamics of land use / cover changes and degradation of Nairobi city, Kenya. *Land Degradation and Development,* 17, 97-108.

Muthoka M.J., Ndegwa M.C., 2014. Dynamism of Land use Changes on Surface Temperature in Kenya: A Case Study of Nairobi City. *International Journal of Science and Research,* 3, 38-41. ID: 020131389

Njoroge J.B.M., Nda'Nganga K., Wariara K., Maina M.G., 2011. Characterising changes in urban landscape of Nairobi city, Kenya. *Acta Horticulturae*, 911, 537–543. http://dx.doi.org/10.17660/ActaHortic.2011.911.63

Obudho R.A., 1999. Urbanization and sub-urbanization processes over time and space. In: Obudho RA (eds), Environment and Development in Kenya. Kenya National Academy of Sciences Publishers, Nairobi, pp. 1-25.

Ogoli D.M., 2003. Predicting indoor temperatures in closed buildings with high thermal mass. *Energy and Buildings,* 35, 851–862. http://doi.org/10.1016/S0378-7788(02)00246-3

Oke T.R., 1973. City size and the urban heat island. *Atmospheric Environment,* 7, 769-779. doi:10.1016/0004-6981(73)90140-6.

Oke T.R., 1981. Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observations. *Journal of Climatology*, 1, 237–254. DOI: 10.1002/joc.3370010304

Oke T.R., 1982. The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society,* 108, 1-24. DOI: 10.1002/qj.49710845502

Okoola R.E., 1980. The Nairobi heat-island. *Kenya Journal of Science and Technology, Series A,1*, 53-61.

Okoola R.E., 1996. *Space-Time Characteristics of the ITCZ over Equatorial Eastern Africa during Anomalous Rainfall Years.* PhD Thesis, University of Nairobi, Kenya.

Okoola R.E., 1999. A diagnostic study of the Eastern Africa monsoon circulation during the northern hemisphere spring season, *International Journal of Climatology,* 19, 143-168. DOI: 10.1002/(SICI)1097-0088(199902)19:2<143::AID-JOC342>3.0.CO;2-U

Ongoma V., Muthama J.N., 2014. A Review and Assessment of Applicability of the Heat Stress Indices in Kenyan Weather Forecast. *Open Journal of Atmospheric and Climate Change,* 1, 17-22.

Ongoma V., Muthama J.N., Gitau W., 2013a. Evaluation of urbanization influences on urban temperature of Nairobi City, Kenya. *Global Meteorology,* 2, 2:e1doi:10.4081/gm.2013.e1

Ongoma V., Muthama J.N., Ng'ang'a J.K., 2010. Effects of urbanization on the Climate of Nairobi City. *Journal of Meteorology and Related Sciences*, 4, 49-60.

Ongoma V., Muthama N.J., Gitau W., 2013b. Evaluation of Urbanization Influences on Urban Winds of Kenyan Cities. *Ethiopian Journal of Environmental Studies and Management,* 6, 223-231. http://dx.doi.org/10.4314/ejesm.v6i3.1

Ongoma, V., 2012. *Evaluation of Urbanization Influences on Urban Climate of Kenyan Cities.* MSc. Thesis, University of Nairobi, Kenya.

Park S., Tuller S.E., Jo M., 2014. Application of Universal Thermal Climate Index (UTCI) for microclimatic analysis in urban thermal environments. *Landscape and Urban Planning*, 125, 146–155. http://doi.org/10.1016/j.landurbplan.2014.02.014

Pauleit S., Liu L., Ahern J., Kazmierczak A., 2011. Multifunctional green infrastructure planning to promote ecological services in the city. In: Niemela J, Breuste J, Guntenspergen G, McIntyre N, Elmqvist T, James P (Eds.), *Urban Ecology: Patterns, Processes, and Applications.* Oxford University Press, Oxford, pp. 272-286.

Robaa S.M. 2003. Urban - suburban/rural differences over Greater Cairo, Egypt. *Atmósfera*, 16, 157-171.

Robaa S.M. 2011. Effect of Urbanization and Industrialization Processes on Outdoor Thermal Human Comfort in Egypt. *Atmospheric and Climate Sciences,* 1, 100-112 doi:10.4236/acs.2011.13012

Ryu H.Y., Baik J.J., 2012. Quantitative Analysis of Factors Contributing to Urban Heat Island Intensity. *Journal of Applied Meteorology and Climatology,* 51, 842-854. DOI: 10.1175/JAMC-D-11-098.1

Schats J., Kucharik J.C., 2014. Seasonality of the Urban Heat Island Effect in Madison, Wisconsin. *Journal of Applied Meteorology and Climatology,* 53, 2371-2386. DOI: 10.1175/JAMC-D-14-0107.1

Shanu K., 2010. An assessment of thermal comfort and user's perceptions of landscape gardens in a high-rise office building. *Sustainable Development,* 3, 3-12. DOI: http://dx.doi.org/10.5539/jsd.v3n4p153

Stewart I.D., Oke T. R., 2012. Local climate zones for urban temperature studies. *Bulletin American Meteorological Society,* 93, 1879-1900. doi:10.1175/BAMS-D-11-00019.1.

Thom E.C., 1959. The discomfort index. *Weatherwise*, 12, 57-60. DOI: 10.1080/00431672.1959.9926960

Toy S., Yilmaz S., 2010. Evaluation of urban-rural bioclimatic comfort differences over a ten-year period in the sample of Erzincan city reconstructed after a heavy earthquake. *Atmósfera*, 23, 387-402.

United Nations, 2001. World Urbanization Prospect; The 1999 Revision. United Nations, Washington, DC. On line at http://www.un.org/esa/population/pubsarchive/urbanization/urbanization.pdf (Accessed on 20/10/2014).

University of East Anglia Climatic Research Unit, Harris I., Jones P.D., 2014. CRU TS3.22: Climatic Research Unit (CRU) Time-Series (TS) Version 3.22 of High Resolution Gridded Data of Month-by-month Variation in Climate (Jan. 1901- Dec. 2013). NCAS British Atmospheric Data Centre. http://dx.doi.org/10.5285/18BE23F8-D252-482D-8AF9-5D6A2D40990C

UNFPA, 2007. *The State of World Population 2007*. United Nations Population Fund, United Nations Publications.

Unger J., 1999. Comparisons of urban and rural bioclimatological conditions in the case of a Central-European city. *International Journal of Biometeorology*, 43, 139-144.

UN-Habitat, 2008. The State of African Cities. A Framework for Addressing Urban Challenges in Africa UN Habitat Nairobi University press, Cambridge UK, and New York NY, USA.

United Nations, Department of Economic and Social Affairs, Population Division, 2014. *World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352).* New York NY, USA.

Unkasevic M., Jovanovi O., Popovic T., 2001. Urban-suburban/rural vapour and pressure relative humidity differences at fixed hours over the area of Belgrade City. *Theoretical Applied Climatology,* 68, 67-73. DOI: 10.1007/s007040170054

Voogt, J.A., 2002. Urban heat island. In: Munn, T., Douglas, A. (Eds.), Encyclopedia of Global Environmental Change. Vol. 3, Causes and Consequences of Global Environmental Change. John Wiley & Sons Ltd., Chichester

Wise A.F.E., 1970. Wind effects due to groups of buildings. In: Proceedings of the Royal Society Symposium Architectural Aerodynamics. Session 3. Effect of Buildings on the Local wind, London. pp. 26–27 February.

WMO, 2015. The Climate in Africa: 2013. WMO-No. 1147. Geneva, Switzerland

Yang P., Ren G., Liu W., 2013. Spatial and Temporal Characteristics of Beijing Urban Heat Island Intensity. *Journal of Applied Meteorology and Climatology,* 52, 1803-1816. DOI: 10.1175/JAMC-D-12-0125.1

Yang W., Seager R., Cane M.A., Lyon B., 2015. The Annual Cycle of the East African Precipitation. *Journal of Climate,* 28, 2385–2404. http://doi.org/10.1175/JCLI-D-14-00484.1

Yilmaz S., Toy S., Yilmaz H., 2007. Human thermal comfort over three different land surfaces during summer in the city of Erzurum, Turkey. *Atmósfera*, 20, 289-297.

Zhang Y.C., Rossow W.B., Lacis A.A., 1995. Calculation of surface and top of atmosphere radiative fluxes from physical quantities based on ISCCP data sets, 1., Method and sensitivity to input data uncertainties. *Journal of Geophysical Research,* 100, 1149-1165. DOI: 10.1029/94JD02747

Zhou L., Dickinson R.E., Tian Y., Fang J., Li Q., Kaufmann R.K., Tucker C.J., Myneni R.B., 2004. Evidence for a Significant Urbanization Effect on Climate in China. *Proceedings of the National Academy of Sciences of the United States of America,* 101, 9540-9544.