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Urban-Rural Temperature Differences in Lagos

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Abstract: In this study, the hourly air temperature differences between City hall (urban) and Okoafo (rural) in Lagos, Nigeria, were calculated using one year of meteorological observations, from June 2014 to May 2015. The two sites considered for this work were carefully selected to represent their climate zones. The city core, City hall, is within the Local Climate Zone (LCZ 2) (Compact midrise) while the rural location, Okoafo, falls within LCZ B (Scattered Trees) in the south-western part on the outskirt of the city. This study is one of very few to investigate urban temperature conditions in Lagos, the largest city in Africa and one of the most rapidly urbanizing megacities in the world; findings show that maximum nocturnal UHI magnitudes in Lagos can exceed 7 °C during the dry season, and during the rainy season, wet soils in the rural environment supersede regional wind speed as the dominant control over UHI magnitude.

Keywords: temperature difference; urban climatology; heat island; Lagos

1. Introduction

Urbanization is a shift in population from rural to urban, *i.e.*, the gradual increase in the proportion of people living in urban areas, and the ways in which each society adapts to the change. In most respects, urbanization is beneficial as it enables increased standards of living: Urban areas create more than 90% of global gross value added [1]. Unfortunately, urbanization also brings with it some negative environmental, social, and economic consequences. The rapid pace of urbanization has been shown to be a global problem present in most developing countries.

The population growth rate will continue to be particularly rapid in the urban areas of less developed regions, averaging 2.4 percent per year during 2002–2030, consistent with a doubling time of 29 years [2]. The concentration of population in cities is expected to continue such that by 2030, 84 percent of the inhabitants of more developed countries will be urban dwellers. The United Nations (UN) predicts that between 2011 and 2050, the world population is expected to increase by 2.3 billion, increasing from 7.0 billion to 9.3 billion [3]. At the same time, the population living in urban areas is projected to increase by 2.6 billion, from 3.6 billion in 2011 to 6.3 billion by 2050 [4]. Thus, the urban areas of the world are expected to absorb all the population growth expected over the next four decades while at the same time drawing in some of the rural population such that nearly all the population growth (64%) will be in the cities of developing countries.

This rapid population growth will largely drive the extent and rate of global environmental changes and many of these changes are related to the climate and atmospheric composition of cities, including the canopy layer Urban Heat Island (UHI) [5], the observed warmth of the urban core compared to its rural surroundings, heat stress, and various forms of air pollution [6]. Climate change will impact living and working environments negatively and create health threats for millions of people in the next decade and beyond [7–11]. The average global temperature is increasing and it is estimated that it will increase further from 1.8 to 4.0 °C (estimated average of 3.0 °C) by the year 2100 [7], depending on actions to reduce greenhouse gas emissions. The extent of local climate change will vary depending on geographic and local meteorological conditions. Increasing local ambient temperature implies higher human exposure to heat such that during hot seasons in hot regions of the world, people who are not able to afford either the cost of air conditioning and other cooling methods or the cost of energy required to run them will be subjected to very severe heat stress and health risks. Both general living environments and working environments will be affected.

The latter may impact workers' health, productivity, and socio-economic development [9,11]. Workers in low and middle income tropical countries are likely to be at the highest risk of excessive heat exposure. Due to anthropogenic activities, the earth's surface is being significantly altered in some manner, and human presence on the earth and use of the land has had a profound effect on almost all meteorological/climate parameters. In order to make the environment more conducive, humans have built structures in urban areas to cater for their needs. These urban structures alter the surface energy budget [12], modify the vertical profile of various atmospheric properties and interact with both local and regional circulation [13].

Urbanization is a major land change driver that leads to significant, often rapid, and near irreversible changes in land systems and land properties. Rapid urbanization and industrialization and the development of more buildings and transportation systems to cater for Lagosians has led to the recognition of human impacts on microclimate, otherwise referred to as the Urban Heat Island phenomenon. The intensity of the Urban Heat Island (Tu-r) can be quantified by the difference in temperature between the central urban site and a rural site. The magnitude of this phenomenon depends on meteorological factors, land use pattern, the population density, and anthropogenic activities of the city [14]. The socio-economic and meteorological impacts of Urban Heat Island in low and high latitude countries are numerous. Some are beneficial while others are detrimental. With respect to human health or thermal comfort, there is a negative impact over low-latitudes, which includes aggravation of heat stress during prolonged heat waves. Heat stress in these regions and seasons are invariably unfavorable for human health. It adds to discomfort and even contributes to death, most especially among the aged already predisposed to certain illness as well as children up to five years old, which are very vulnerable to the vagaries of weather [15]. The Urban Heat Island effect over the cities, which results in heat waves, can also promote the chemical break-down of some building materials by weakening them [16]. The study of Urban Heat Island (UHI) is important as it affects health, comfort and energy consumption for heating and cooling urban buildings in cities.

Literature Review

Research on the modification of local climate through urbanization is not new. According to Landsberg [17], Luke Howard is credited to have carried out the first scientific study of inadvertent urban climate modifications in 1818, by comparing the temperature records of a London city weather station with that of Kew Gardens (then a rural station) and found that the city station was warmer.

The importance of the Urban Heat Island [18] has become increasingly recognized by planning authorities during recent years (e.g., Mayor of London, [19]. The temperature increment generated by European cities like London was found to lead to an increased mortality rate during hot summer periods and with climate change, will lead to greater demands for cooling the internal environment. However, the winter urban temperature increment has benefits: leading to lower mortality rates and lower energy consumption due to warmer nighttime temperatures and reduced heating. A review of urban climate research by Jauregui [20] shows that out of all of the UHI studies carried out during the period 1968–1980, those in tropical regions accounted for only 2%, this proportion rose to 4% in the mid-1980s. According to Wienert [21] out of the UHI studies carried out in 223 cities, only 17% were in the tropics. By the mid-2000s, Roth [22] opined that only basics of the physical processes operating in the atmosphere of tropical climates are available because of the limited range of urban morphologies of cities studied. The situation is not different in Nigeria, Africa's most populous country, as some studies have been conducted in this regard.

Back in the 1980s, Oguntoyinbo [23] was of the opinion that a slow rate of urbanization and industrialization and the general lack of expertise are what led to a lack of interest in urban climatology in the tropics. Oguntoyinbo [24] examined the impact of urbanization on the climate of Ibadan. Air temperature and relative humidity data were collected for certain synoptic hours across the city during the daytime using simple Thermohygrographs and whirling hygrometers. These data were compared with data from the observatory at the Ibadan airport. The result shows that 3.0 °C higher air temperatures and 7% lower relative humidity in the city were recorded during the day time. In his later work, he used an Assman Aspirated psychrometer and a whirling psychrometer in assessing temperature and relative humidity observed by using mobile traverses in different seasons across the city of Ibadan. The study revealed that there is a significant relationship between UHI development and cloud cover and building density. A UHI of 2.2 °C was recorded in the afternoon in March (representing the dry season) in the heavily built-up areas in Oja'ba, Oje and Agbokojo; this dropped to 0.8 °C in the early morning. In August (representing the short dry season), a UHI of 3.3 °C was recorded in the afternoon and it decreased to 1.7 °C in the early morning. In November (representing the Harmattan period), 3.6 °C was recorded in the afternoon and it dropped to 1.6 °C in the early morning. The study concluded that elevation, vegetation and open space have negative effects on UHI development.

Ojo [25] studied the spatial and temporal variation of temperature across Lagos city using temperature data taken from transect across the city. His findings showed a UHI effect of 2 °C to 4 °C in the zone of dense traffic and main traffic corridors of Mushin/Oshodi areas of the city at noon or in the late afternoon. Land-use energy balance relationships in the city were also examined. Later, [20] in Lagos discovered that the UHI effect is higher in the morning on the islands adjacent to the Atlantic Ocean, due to marine influence. But for the rest of the city, it is conditioned by the characteristics of the land use type. Oguntoyinbo [23] discovered that UHI varies with seasonal variation and time of day in Ibadan. UHI was most marked at the height of the dry season (March), especially in the afternoon, ranging between 5 °C to 7.5 °C in the city center and dropping to 0.8 °C in the early morning. During the wet season, the recorded mean values of the UHI ranged from 1 °C to 3 °C, while in the Harmattan season it was about 1 °C to 5 °C.

In Nigeria, the first comprehensive urban climate study was that of Adebayo [26], who analyzed the spatial, diurnal and seasonal characteristics of global radiation, surface albedo, net longwave radiation and latent sensible fluxes of energy for Ibadan city. The study was based on data collected on a daily basis (06:00 h–18:00 h GMT) for one year from 20 stations located all over the city. It showed that there was a decrease of radiation (about 14%) in the urban center, which was attributed to the effects of pollution veil and the reduced sky view factor within the canopy. There was also a decrease in surface albedo and an increase in net radiation both at the city center when compared to those of the rural areas. The increase in net radiation is attributed to an increase in the amount of energy absorbed from surface and long wave radiation by atmospheric contamination. The study also indicated a decrease in relative humidity (about 5%) in the city center compared with that of the rural areas during the wet season, whereas during the Harmattan season, the decrease was about 8%. A UHI effect of 1 °C–1.5 °C was observed at the city center during the wet season; it ranged from 2.5 °C to 3 °C during the Harmattan while in the middle of dry season, a UHI effect of up to 8 °C was observed.

Adebayo [27–29] identified the following as causes for the city-country temperature differences (UHI effect): (i) Reduction in albedo (thermal reflection), which causes more heat to flow to and from the earth's surface; (ii) The presence of the air pollution veil; and (iii) Urban canyon, which traps the heat radiation. In their study in Akure, Balogun *et al.* [30] showed that the nocturnal heat island was more frequent than the daytime heat island as it exists from less intense to higher intensity categories throughout the study period. They also reported that the nocturnal heat Island intensity was stronger during the dry season and lower intensity daytime heat Island exists throughout the day except for a few hours in the months of November and December that exhibited a reverse thermal contrast. The daytime heat island was observed to be more intense in the wet months than the dry months, which may be caused by the evaporative cooling of wet surfaces and on average, the urban/rural thermal differences were positive, varying from 4 °C for nocturnal hours during dry months to an approximate value of 2 °C around noon during wet months [30,31]. More recently, Ayanlade and Jegede [32] explored the role of remote sensing on the intensity of the daytime surface Urban Heat Island of the Lagos metropolis using a time series of Landsat data, from 1984 to 2012, and reported that source landscape contributes positively to the intensity of SUHI in the Lagos metropolis. Their results further showed a general increase in mean LST during the periods of study from 1984 to 2012.

It is evident from the literature that apart from the studies of [25] and [23], there are virtually no studies dealing with the issue of air temperature differences/UHI in Lagos using observation data. This is not disconnected from the fact that Lagos, being a coastal city, also faces the challenge of urban flooding and sea level rise and therefore, research attention has been directed towards this challenge. For instance, in of all the papers presented during the Lagos State Government annual climate change summits for the past seven years (2009–2014) by both local and international scholars, the topical issue of the Urban Heat Island has never been addressed despite the huge climate, energy use and health implications of UHI. More so, the Lagos Climate Change Policy document (2012–2014) addressed the effects of climate change on flooding, water shortages, food insecurity, and increased disease incidences together with associated social disruption without consideration of UHI in the policy document.

In this study, we present urban-rural temperature differences and the effects of synoptic observations on the UHI in Africa's most urbanized coastal megacity of Lagos. Hitherto, there are only very few studies that have addressed this issue in the study area in particular and Nigeria in general using remotely sensed data or observations of meteorological parameters. This study aims at investigating the existence, seasonal variation and intensity of the Urban Heat Island; the excess of the urban over rural air temperatures in Lagos. The result of this study will provide useful input for considerations in the future urban development/renewal and planning policy of a climate-smart city of Lagos.

2. Methods

2.1. Study Area

Lagos is the smallest state in Nigeria by landmass. The geographical area of Nigeria that is defined as metropolitan Lagos is unique in many ways. It is the 6th largest city in the World and the largest city in sub-Saharan Africa. It is composed of 20 local government areas (LGA), of which 16 form the high-density metropolitan region [33]. The city of Lagos lies in south-western Nigeria, on the Atlantic coast. It is located at longitude 2°42′E and 3°42′E and between latitudes 6°22′N and 6°42′N (see Figure 1). On this stretch, lies the Lagos Lagoon with long coastal sand spits or sand bars. Badagry Creek flows parallel to the coast for some distance before finding an exit through the sand bars to the sea. The southern boundary of the state is formed by the 180-km long Atlantic Coastline while its northern and eastern boundaries are shared with Ogun state.

The region falls within the tropical rain forest belt and the eco-zones are predominantly wetlands and rain forest. The dominant vegetation of the State is the tropical swamp forest consisting the freshwater and mangrove swamp forests, both of which are influenced by the double rainfall pattern of the State, which makes the environment a wetland region, hence, the reference to Lagos as an environment of aquatic splendor. Its wetland environment is characterized by rich alluvial and terrallitic red-yellow soil, on which would be found dense luxuriant undergrowth, climbers, epiphytes and tropical hardwoods. The vegetation types found outside the urbanized area are mostly secondary forest, mangrove swamps, freshwater swamps and cultivated crops [34].

The interaction between the warm, humid maritime tropical air mass and the hot and dry continental air mass from the interior gives the state two seasons; a wet season from April to October and a dry season from November to March [35]. The mean annual rainfall of the state is roughly 1, 657 mm. The rain falls every month of the year with the highest amount in the month of June as a result of strong rain-bearing southerly wind prevailing in the area from the Atlantic Ocean. The air is very humid throughout the year, with monthly average maximum temperatures ranging from 28.6 °C in July/August to 33.7 °C in February/March (see Figure 2).

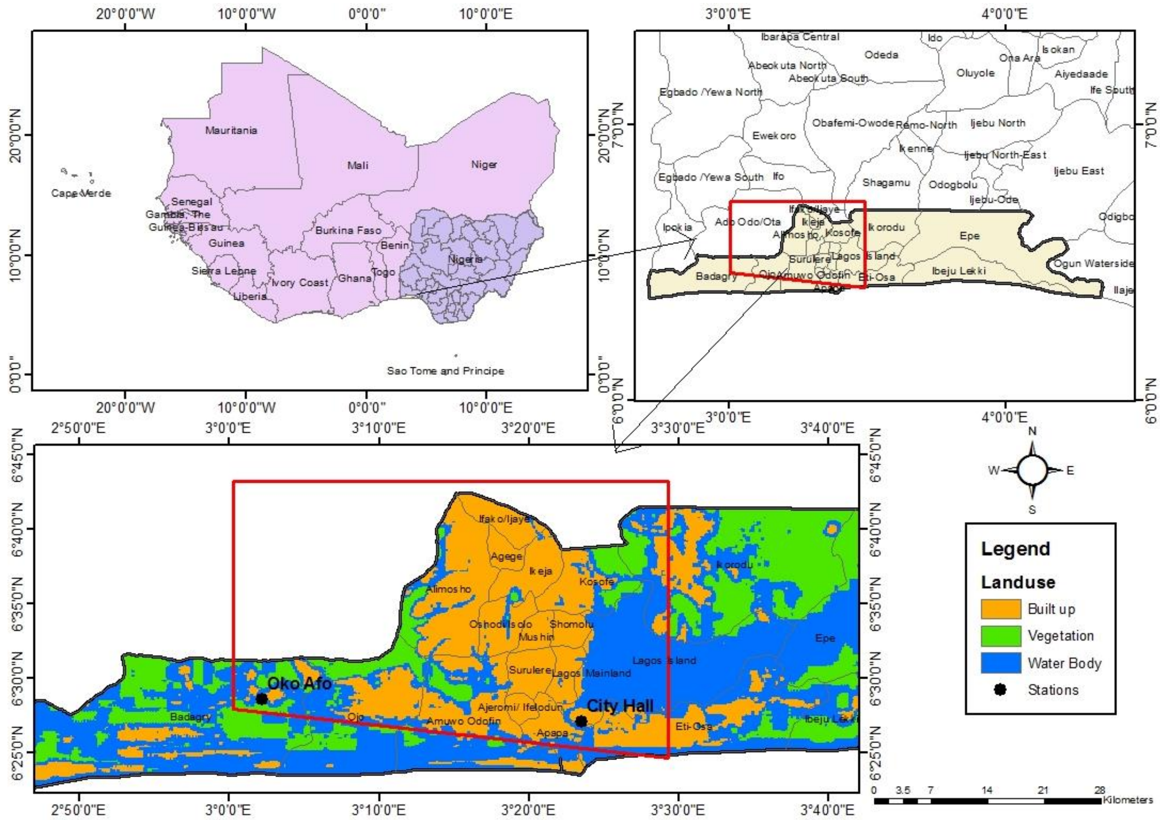
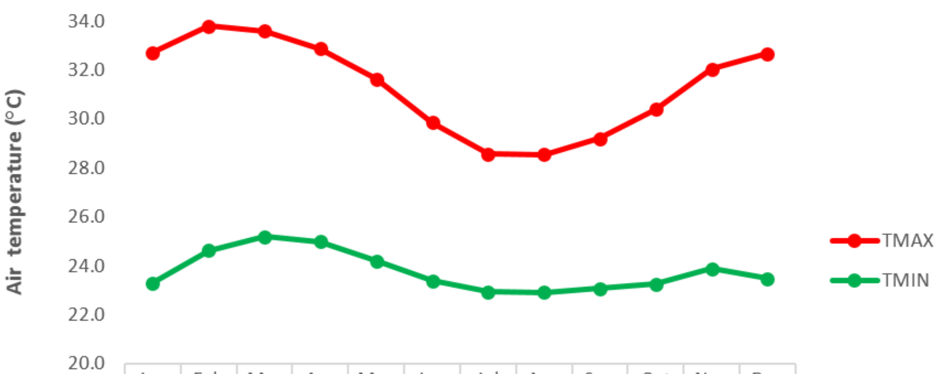


Figure 1. Map of the study location.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TMAX	32.7	33.8	33.6	32.9	31.6	29.9	28.6	28.6	29.2	30.4	32.0	32.7
TMIN	23.3	24.6	25.2	25.0	24.2	23.4	22.9	22.9	23.1	23.3	23.9	23.5

Months

Figure 2. Mean monthly Air Temperature in Lagos (1981–2013).

Lagos has a wet equatorial type of climate influenced by its nearness to the equator and the Gulf of Guinea and is characterized by a deep and poorly drained soil. The drainage system of the State is characterized by a maze of lagoons and Waterways, which constitute about 22% or 787 sq km of the state's total landmass. The major water bodies are the Lagos and Lekki 8 lagoons, Yewa and Ogun Rivers. Others are Ologe Lagoon, Kuramo Waters and Badagry, Five Cowries and Omu Creeks. Water bodies and wetlands cover over 40 percent of the overall land area of the state and additional 12 percent is subjected to seasonal flooding [35]. The topography of Lagos consists of low-lying coastal beaches, extensive inland lagoons and depressions and marsh and mangrove wetlands at elevations of 0.2 m and upland areas with moderately drained soils and an elevation of 2 to 50 m above sea level [36].

Currently, Lagos has an estimated population of over 21 million people and this is expected to grow to over 23 million by 2015 [33,37] using an annual growth rate (AGR) of 3.2%. Over fifty per cent of Nigeria's electrical power generation is consumed by metropolitan Lagos. More than half the number of vehicles in Nigeria is concentrated on its network of roads. Eighty percent (80%) of the population of Lagos State resides in the 37% of the land and the State's economic activities are concentrated in the metropolis, which served as the seat of the former Federal capital of Nigeria until 1991 and is currently the seat of Lagos State Government.

According to the Master Plan for Metropolitan Lagos (MPML) the urban land area was approximately 172 km^2 in 1976 [38,39]. The major part (97.5%) of this land was in the contiguous built-up area, which generally fell within a broad triangle having a base of about 30 km along the Bight of Benin extending from Lekki, Maroko and lkoyi westwards to Ojo and Ijanikin. The north-south part of the triangle covers a distance of about 26 km from Lagos Island to Alagbado at the southern and northern ends, respectively. A detached portion of the Lagos urban development area surrounds Ikorodu. This 2.5% of the total metropolitan area is separated from the contiguous area of the metropolis [39]. Lagos State has lots of housing estates comprising mainly midrise and high-rise buildings in the metropolitan areas with paved land cover. Construction materials include stone, brick, tile, and concrete materials. However, a major feature of Lagos' landscape is the proliferation of slums and informal settlements. These evolved in response to government's inability to provide adequate housing for the teeming population. These slums and informal settlements provide accommodation for the majority of the people and are usually the first point of call for new migrants [40]. As of 1991, the World Bank Urban Renewal Project identified 42 slum communities in Lagos State [41]. The number of slums in Lagos is now estimated to have increased to more than 100 due to the inadequacy of private and public institutions to provide housing for the increasing population [40]. The slum areas are largely unpaved, low-rise buildings with thatch, wooden and zinc roofs and mud and brick walls. Most of the slums are located close to open water bodies such as the tributaries of rivers. Others are located very close to lakes, reservoirs, and lagoons, which abound in the state.

2.2. Weather Stations

A basic automatic weather station (BWS200) from Campbell Scientific was installed on the rooftop at Oshodi to collect synoptic data of the city. Measurement of daily air temperature with Thermocron ibutton data loggers logging at 15-min time intervals for one year (June 2014–May 2015) was carried out at City hall and Okoafo. The generated data were then computed into one-hour averages for ease of reporting. City hall is in the urban core and Okoafo is in the rural area close to Badagry, and the automatic weather station was located at Oshodi and was set up for synoptic observation (see Figure 3).

Table 1 shows the site characteristics of each of the stations classified based on the local climate zone classes [42]. The automatic weather station (AWS) (LCZ 2) is located on the rooftop of the official building of the Nigerian Meteorological Agency in Oshodi, central to the rural station (LCZ B) at Okoafo, a lightly wooded landscape of deciduous trees and tall grasses with mostly pervious (low plants) land cover. Urban station (LCZ 2) at City hall, is located in a dense mix of midrise buildings (3–9 stories) with few or no trees. Land cover is mostly paved and visible stone, brick, tile, and concrete construction materials.

The AWS was set up for synoptic observation of wind speed, wind direction, solar radiation, air temperature, Humidity, rainfall and barometric pressure were recorded at 15-min intervals over Lagos while the data loggers, Hygrochron ibuttons, and DS1923 model manufactured by maxim-ic were used to obtain the spatial temperature (Ta) and relative humidity (RH) data at the two selected sites. The data logger has a resolution of 0.05 with a measuring range of −20 °C to +85 °C and accuracy of ±0.5 °C. The stations were set up on the following dates, 20 May 2014 (Okoafo-rural), 21 May 2014 (city hall-urban) and 22 May 2015 (Oshodi-synoptic).

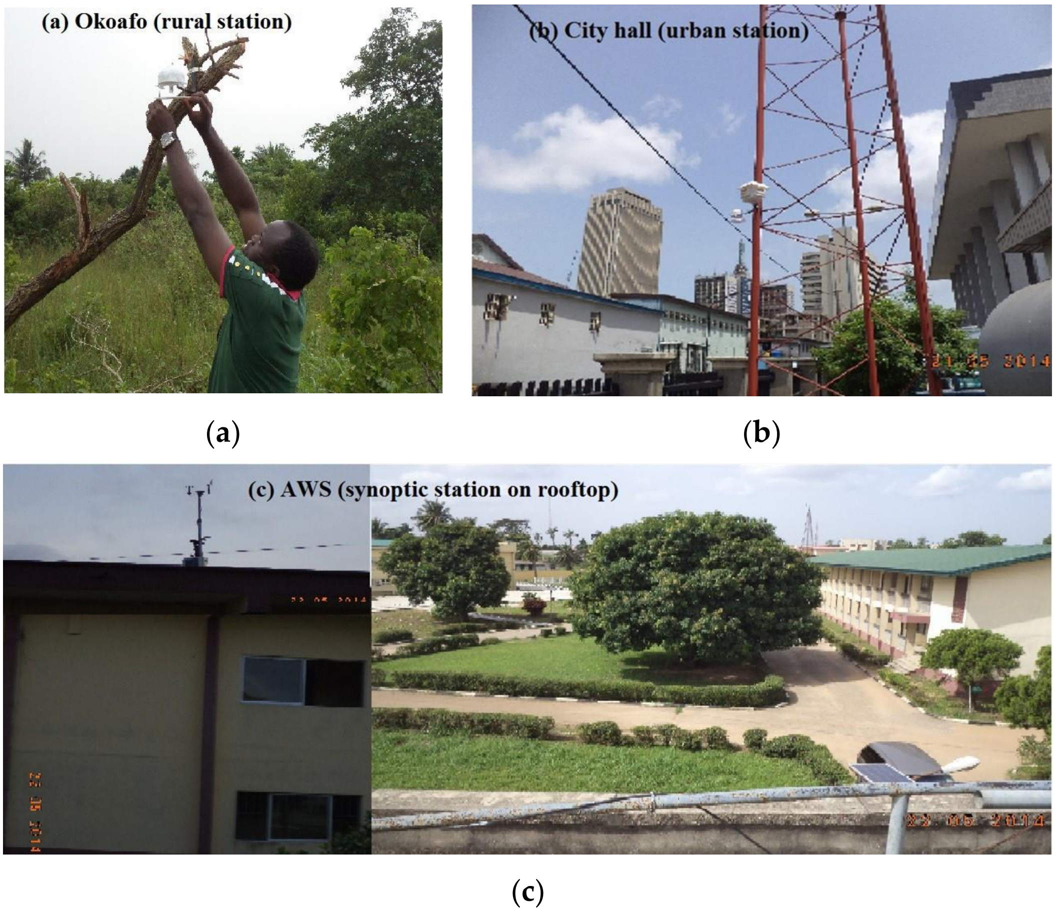


Figure 3. Datalogger sites in (**a**) Rural (Okoafo); (**b**) Urban (City Hall) and (**c**) Automatic Weather station (AWS) located on the rooftop of a one storey building at the Nimet premises in (Oshodi) used for the study (see Appendix for Google images of the locations).

Table 1. Summary of site characteristics.

Station	Site	Lat (N)	Long (E)	Elev Area (m)	Elev Sensors (m)	LCZ	Description
1	Oshodi (AWS)	06°32.40′	003°20.46′	25	31	5	Open Midrise
2	Okoafo (OK)	06°28.52′	003°02.15′	9	3	B	Scattered Trees
3	City Hall (CH)	06°27.02′	003°23.53′	11	4.5	2	Compact Midrise

* LCZ is a local climate zone, as defined by Stewart and Oke (2012).

Firstly, the monthly mean value of air temperature in the City hall and Okoafo area are presented. Secondly, the hourly temperature differences between the City hall and Okoafo are calculated, producing the hourly values of the Urban Heat Island, ΔTu-r. The Urban Heat Island was obtained for each day in each month to produce the diurnal pattern. Lastly, the synoptic data on wind speed and solar radiation were plotted against the UHI to ascertain their effects on the UHI intensity in the area.

3. Results and Discussion

3.1. Distribution of Mean Temperature over Lagos (June 2014–May 2015)

Figure 4 shows the seasonal distribution of Tmean at City hall and Okoafo in (a) JJA, (b) SON, (c) DJF and (d) MAM. The air temperatures (Tmean) in the City hall area were 27.1 °C, 26.1 °C and 26.1 °C, respectively, during the JJA. It is seen that the mean air temperature was higher in the month of June than the remaining two months of the season, which recorded the lowest mean air temperature values for the study period. This could be attributed to the prevailing conditions of the sky and wind speed intensity. During the transition to the dry season period, SON, lower values of mean air temperature were recorded in City hall. The values recorded were 26.3 °C, 27.4 °C and 29.3 °C. The temperature pattern during the dry season period, DJF witnessed a slight increase in mean air temperature from the preceding season with values of 29.8 °C, 27.9 °C and 30.0 °C, respectively. The MAM period shows that mean air temperatures values were higher for this season during the study period, being 30.0 °C, 30.4 °C and 28.4 °C, respectively. Although the monsoon starts in this period, its effects are not fully felt on the air temperature until its peak between the months of July–August.

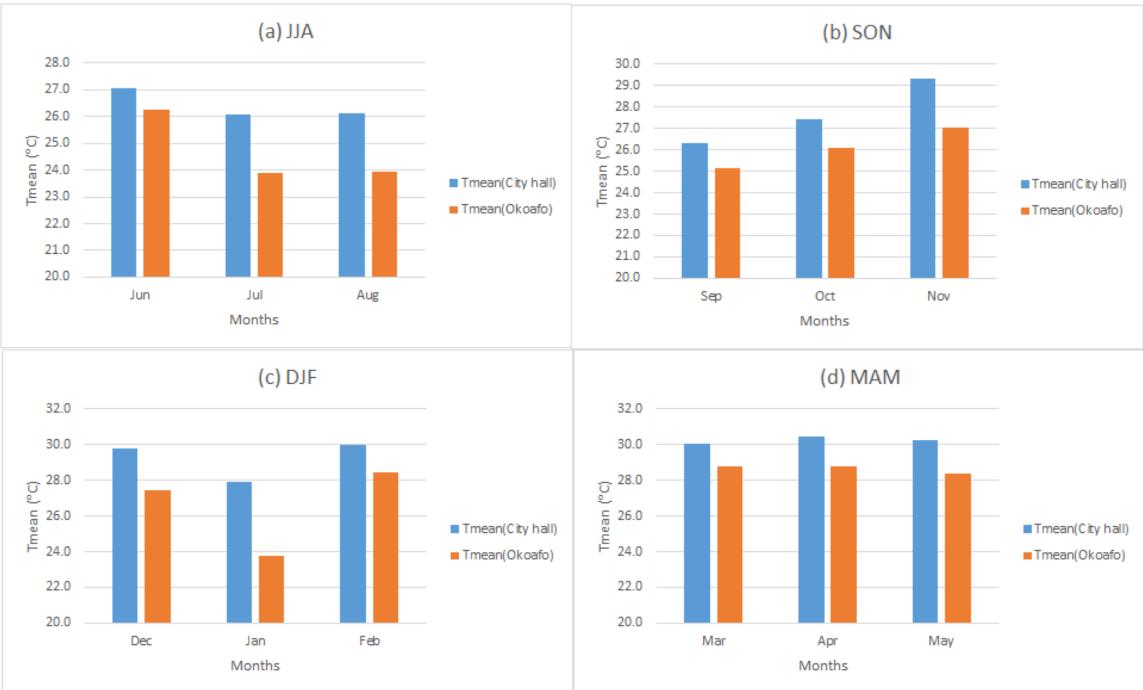
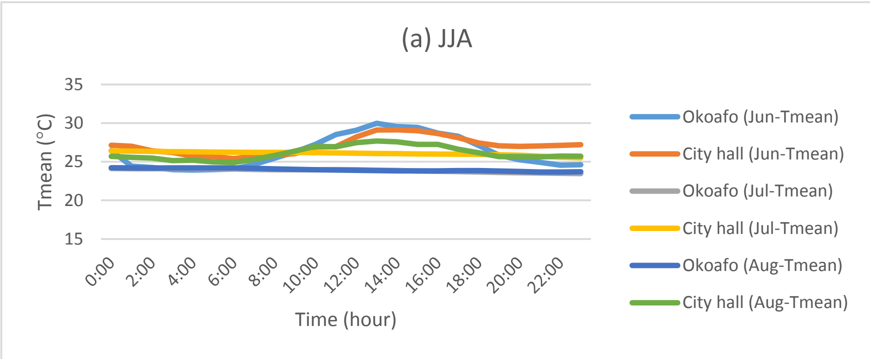
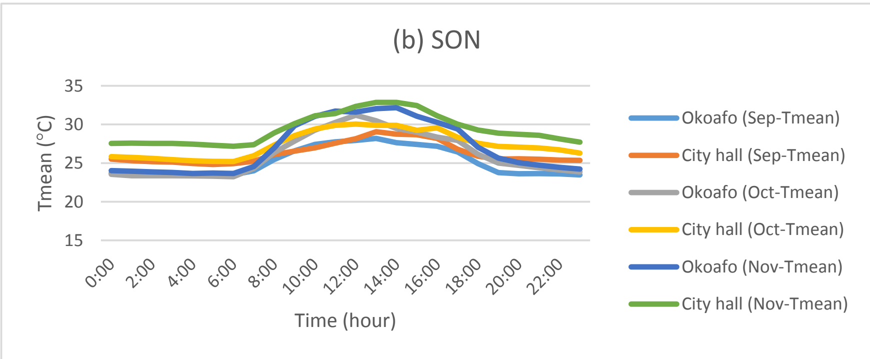


Figure 4. Seasonal distribution of Tmean at City hall and Okoafo in (**a**) JJA; (**b**) SON; (**c**) DJF and (**d**) MAM.

At Okoafo, the mean air temperature pattern shows a similar pattern to that recorded in City hall. Although the lowest values of mean air temperature were recorded during JJA, the month of June recorded a value higher than the months of July and August. The Tmean values for the period are 26.3 °C, 23.9 °C and 24.0 °C, respectively, for each month. During the transition period of SON, there was a slight increase in the Tmean values recorded. The Tmean values for SON were 25.2 °C, 26.1 °C and 27.0 °C. The mean air temperature showed another slight increase in the amount recorded during the dry season months (DJF) apart from the month of January, which recorded a lower value. The values of Tmean for DJF were 27.5 °C, 23.8 °C and 28.4 °C. The observation of low Tmean value for the month of January could be attributed to the effect of the Harmattan caused by the north-easterly wind prevailing over the season and the moisture content of the air because of the availability of vegetation. The MAM period recorded the highest mean air temperatures. The values recorded were 28.8 °C, 28.8 °C and 28.4 °C, respectively, for each month in the period. In both City hall and Okoafo, the air temperature pattern in the month of June being the first month in JJA shows that it still retains a characteristic pattern of the MAM period. The possible effect of the low moisture content from the sea to the land cannot be ruled out.

Figure 5 shows the diurnal pattern of Tmean at City hall and Okoafo in (a) JJA, (b) SON, (c) DJF and (d) MAM. In Figure 5, the diurnal pattern of the mean air temperature shows that generally temperatures begin to rise in the study area after 07:00 h until peaking at midday and gradually starts dropping until 18:30 h. However, the months of July and August during JJA did not quite follow this pattern during the period of study. This could also be attributed to the monsoon since it is at its maximum by August and the possibility of a cloudy sky is almost certain. This attenuates the effect of solar radiation on heating up of the ground surface, thereby reducing the values of the air temperature. Over Nigeria, the common consensus is that during the monsoon season, the country receives moisture from the tropical Atlantic via low-level southwesterly flow across her southern coast. At the surface, this moist southwesterly airstream can penetrate beyond the country as far as the southern fringes of the Sahara Desert near 20°N [43].





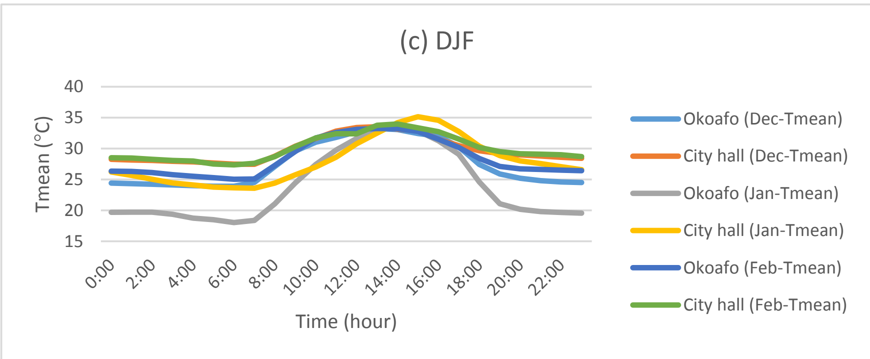


Figure 5. *Cont.*

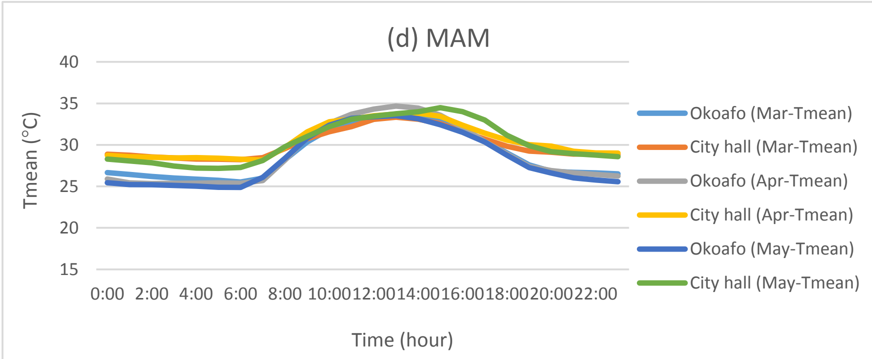


Figure 5. Diurnal pattern of Tmean at City hall and Okoafo in (**a**) JJA; (**b**) SON; (**c**) DJF and (**d**) MAM.

3.2. Seasonal Pattern of the UHI

Figure 6 shows the seasonal variation of mean UHI in (a) JJA, (b) SON, (c) DJF and (d) MAM. From Figure 6, it is evident that during JJA, the mean UHI in Lagos is higher during the day than the night period except for the month of June. This could be linked to excess soil moisture prevailing over the rural site in contrast to the urban site as the presence of wet soils and vegetation delays surface and near-surface heating, creating a large daytime heat island magnitude following sunrise. However, UCI (inverse heat island) is observed during the day in the month of June unlike the other rainy season months of July and August. The month of June also shows an unusual trend of delay between the rain and its effect on the UHI. This is due to the low moisture content moving from the Atlantic Ocean to the land because at this period, the highest mean UHI intensity values at during the day were 4.4 °C and 3.8 °C in July and August, respectively, while the cool island effect was −1.6 °C in June. During the night time, the highest mean UHI was 2.6 °C.

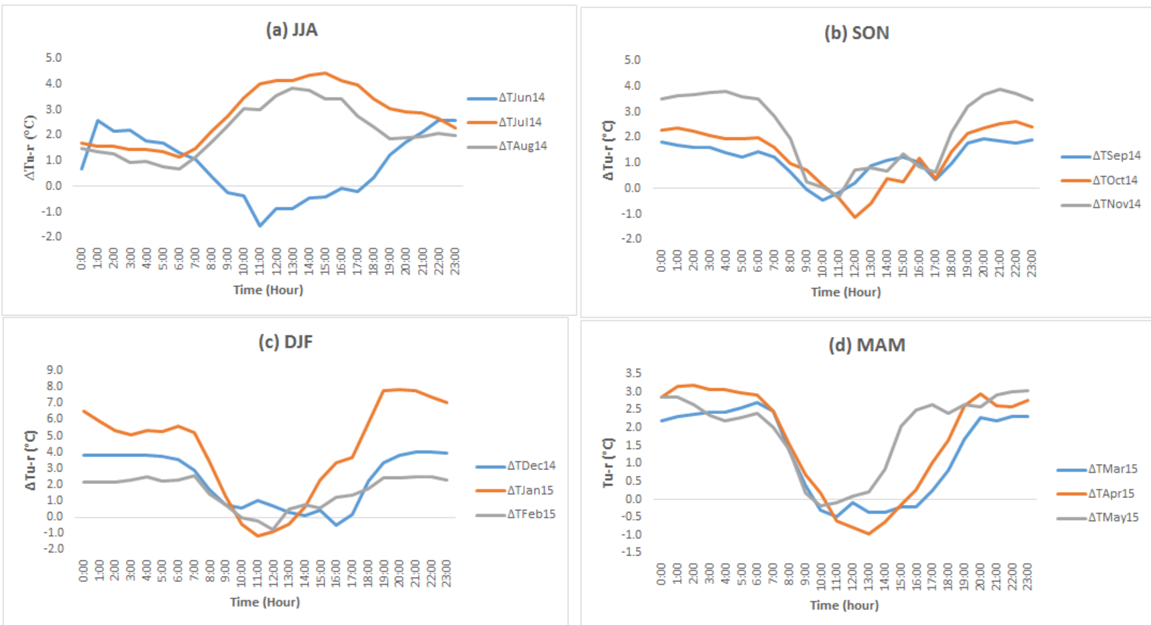


Figure 6. Seasonal variation of mean UHI in (**a**) JJA, (**b**) SON; (**c**) DJF and (**d**) MAM.

In SON, the day time was cooler than the night period. The daytime UCI was −1.1 °C at noon but there was a more prolonged heat island effect from 21:00 h to 04:00 h , which ranged between 3.8 °C to 3.9 °C. Being a transition to the dry season period, the UCL effect during the day could be linked to the presence of vegetal cover in the rural site, and modification of the moisture availability. The nighttime difference can be attributed to the geometry and urban form in the urban site.

DJF is the dry season period with the Harmattan. The Harmattan is a dry and dusty northeasterly trade wind that blows from the Sahara Desert over the West African subcontinent into the Gulf of Guinea between the end of November and the middle of March (winter). During this period, relative low mean UHI and UCI prevail during the day but high night time heat island is traceable to the urban built forms, pavement and construction materials and the dense mixture of tall buildings in the city centre; as such, the cool effect of the Harmattan is not felt at night. The stronger UHI intensity in the month of January especially from 19:00 h (7.8 °C) to midnight (7.0 °C) can be traced to effects of localised change in weather conditions. First, the Harmattan period is calmer than the wet period [44]; relative calmer conditions lead to the accumulation of heat within the atmospheric boundary layer [26]. Secondly, whereas the rainy season is cloudy, the Harmattan season is generally cloudless; cloudlessness allows for the direct uniform heating of the surface, therefore leading to higher heat island intensity [26]. Apart from the localised change in weather that introduced stronger UHI in January, the UHI during the nighttime in December and February was moderate with the strongest intensity being 3.9 °C and 2.3 °C in December and February, respectively. This result is congruent with Adebayo [26], who reported a higher amount of 'heat island' intensity during the Harmattan season than the rainy season in Ibadan metropolis, Nigeria in 1987.

MAM is another transition period leading to the rainy season in Nigeria with a less strong UHI pattern like the preceding season. Strongest UHI intensity was observed in the late hours of the day, *i.e.*, 18:00 h to midnight through early hours of the morning. Highest UHI intensity was between 2.9 °C to 3.0 °C for the period with a cool island effect of −1.0 °C at 13:00 h. The urban surface at this period is warmer than the rural site because of the attributes of the paved surface compared with the much-vegetated surface with relatively little or no paved surfaces This is congruent with Balogun [45], who observed maximum UHI in the dry season in Akure between 18:00 h to 22:00 h. However, the result also shows that maximum UHI occurs during the daytime in the rainy season at 12:00 h (noon) (6.9 °C) and 16:00 h (6.3 °C) local time with a gradual decrease between this period and from 4.8 °C at 17:00 h to 1.8 °C at 0:00 h (midnight). A similar result was obtained by Balogun *et al.* [43] in Akure; Oguntoyinbo [22] and Oke [46] in Mexico.

3.3. Noon and Midnight UHI Pattern

Figure 7 shows the noon and midnight variation of maximum UHI in Lagos. From Figure 7, the UHI effect is observed at midnight in all months of the year with the maximum of 6.5 °C in January (dry season) and a minimum of 0.7 °C in June (rainy season). However at noon, both the UHI and UCI effect is observed. UCI at noon was observed in six months with highest UCI of −1.1 °C in October and the UHI effect at noon was observed in the remaining six months of the year with the highest value of 3.6 °C in August. This is as a result of the excess heat retention of the urban form and pollution during the day, which is later released at night.

3.4. Effect of Synoptic Observation on UHI Pattern

Figure 8 shows the effect of solar radiation on the UHI pattern in (a) JJA, (b) SON, (c) DJF and (d) MAM. In Figure 8a–d, the solar radiation pattern is the same, sunrise at 7:00 h local time and sunset at 19:00 h local time. The time period between sunrise and sunset is about 12:00 h throughout the season. It should be noted that solar radiation is used here as a substitute variable for cloud cover (*i.e.*, low radiation values suggest greater cloud cover and vice versa). The cloud cover is observed universally closely correlated with UHI magnitude. It is also evident that apart from the monsoon months of July and August, solar radiation has an inverse relationship with the UHI pattern; daytime is when the solar radiation is highest (less cloud cover) but the daytime temperature difference between the urban and the rural site is lower, in most cases resulting in a cool island effect. However, the UHI intensity starts increasing about 4 h to sunset and this increases further after sunset, making the night time temperatures higher in the urban site. This is evidence that it is the heat that is trapped in the urban site due to the urban form, the building configuration patterns as well as contributions from dense, impervious surfaces that increase the amount of energy that is absorbed and eventually stored in the city; low-albedo surfaces, such as dark rooftops and asphalt roadways; anthropogenic heat sources such vehicular and building emissions could result from cooling systems [47–49].

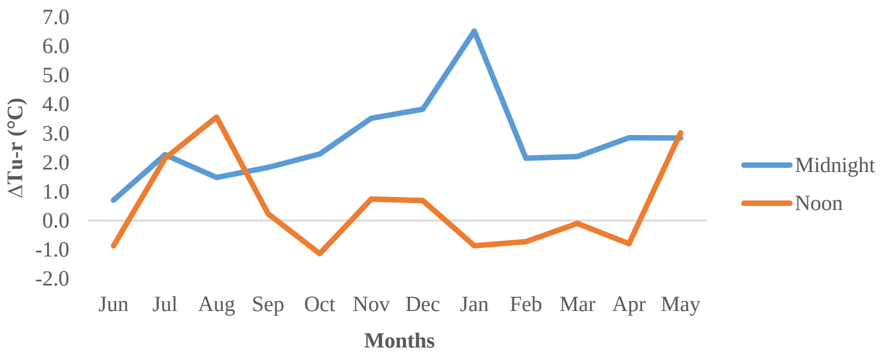


Figure 7. Noon and Midnight Variation of Maximum UHI in Lagos.

Another visible pattern of solar radiation is that it has a bimodal peak reaching the first peak at 12:00 and the second peak at 16:00 h with a reduction at 14:00 h, which could be as a result of the presence of aerosol and pollutants that are capable of causing scattering of the incoming solar radiation and the dilution of heat due to intense vertical mixing in the midday boundary layer. In the four seasons presented, the intensity of the UHI is stronger at night with a cool island effect for a few hours in the day apart from July to August.

Figure 9 shows the effect of wind speed on the UHI pattern in (a) JJA, (b) SON, (c) DJF and (d) MAM. In Figure 9a–d, the seasonal pattern of the UHI and the effect of wind speed shows that a decrease in the amount of wind speed (light wind) favours the maximal mean heat island intensity and vice versa. Wind speed is strongest during the day but weaker at night in all seasons but lower UHI intensity and few hours of UCL is observed. The strong wind speed during the day at the urban site moderating the temperature at this time could be attributed to localized cool sea breeze from the Lagos Lagoon and the Atlantic Ocean unlike the rural site several kilometers inland. The peak of the mean wind speed is between 14:00 h to 16:00 h . In JJA season, a windy condition of 3.5 m/s resulted in a reduction of the cool island of −0.2 °C in June but with a light wind of 1.7 m/s, the UHI intensity was 2.7 °C and this was more evident at night. In SON season, September had the highest mean wind speed of 3.8 m/s with a corresponding low UHI intensity of 1.4 °C. A similar pattern is observed in DJF and MAM seasons where UHI is stronger at night with calm wind.

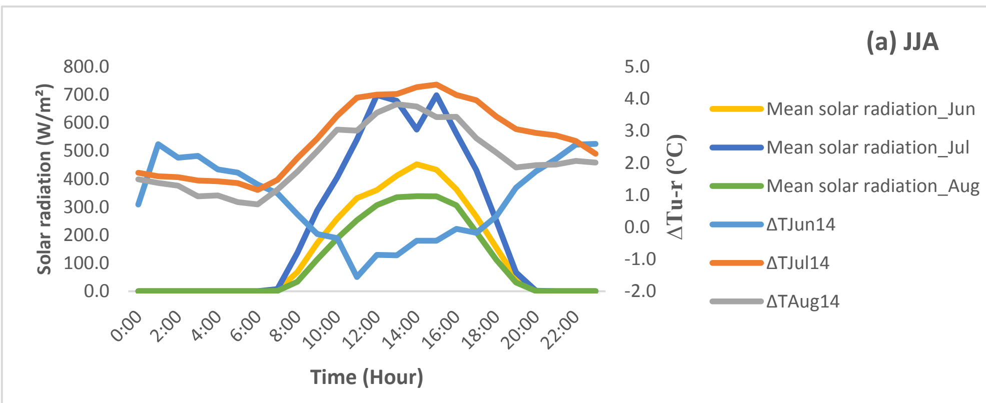


Figure 8. *Cont.*

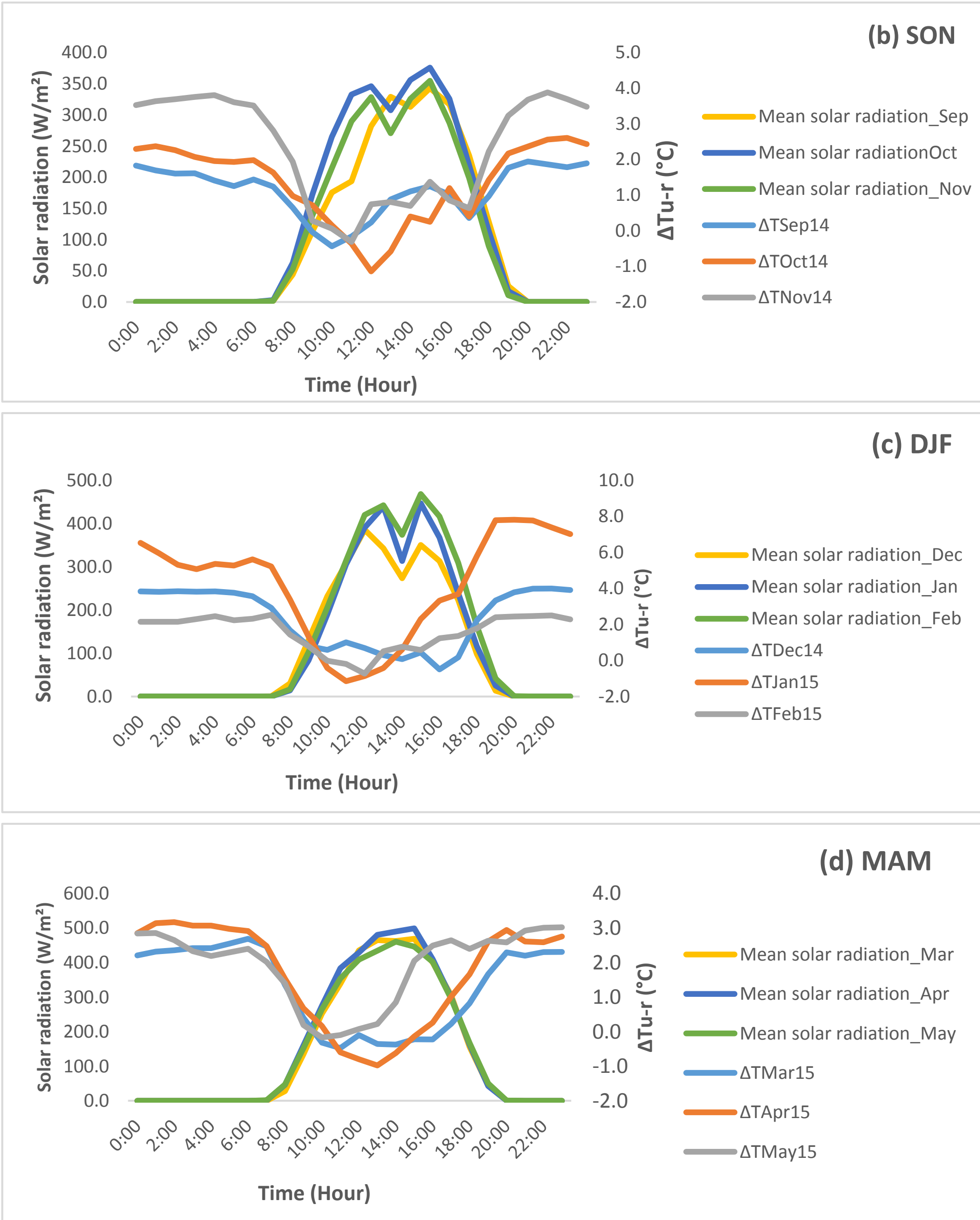


Figure 8. The effect of solar radiation on UHI pattern in (**a**) JJA; (**b**) SON; (**c**) DJF and (**d**) MAM.

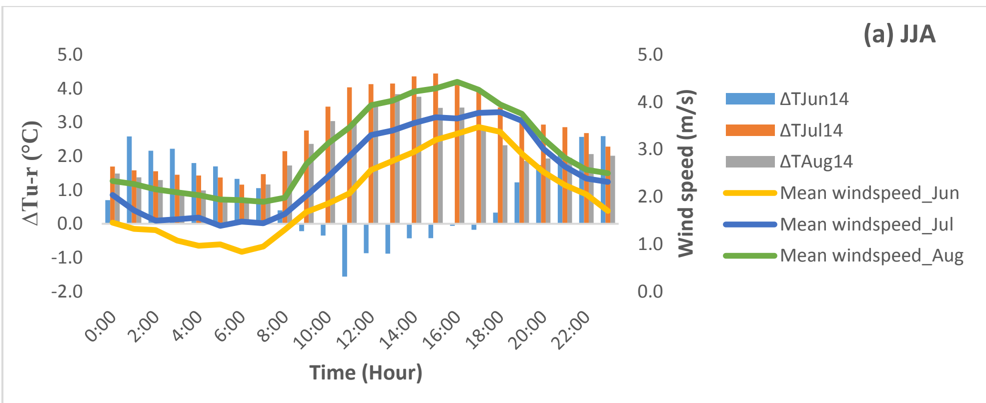


Figure 9. *Cont.*

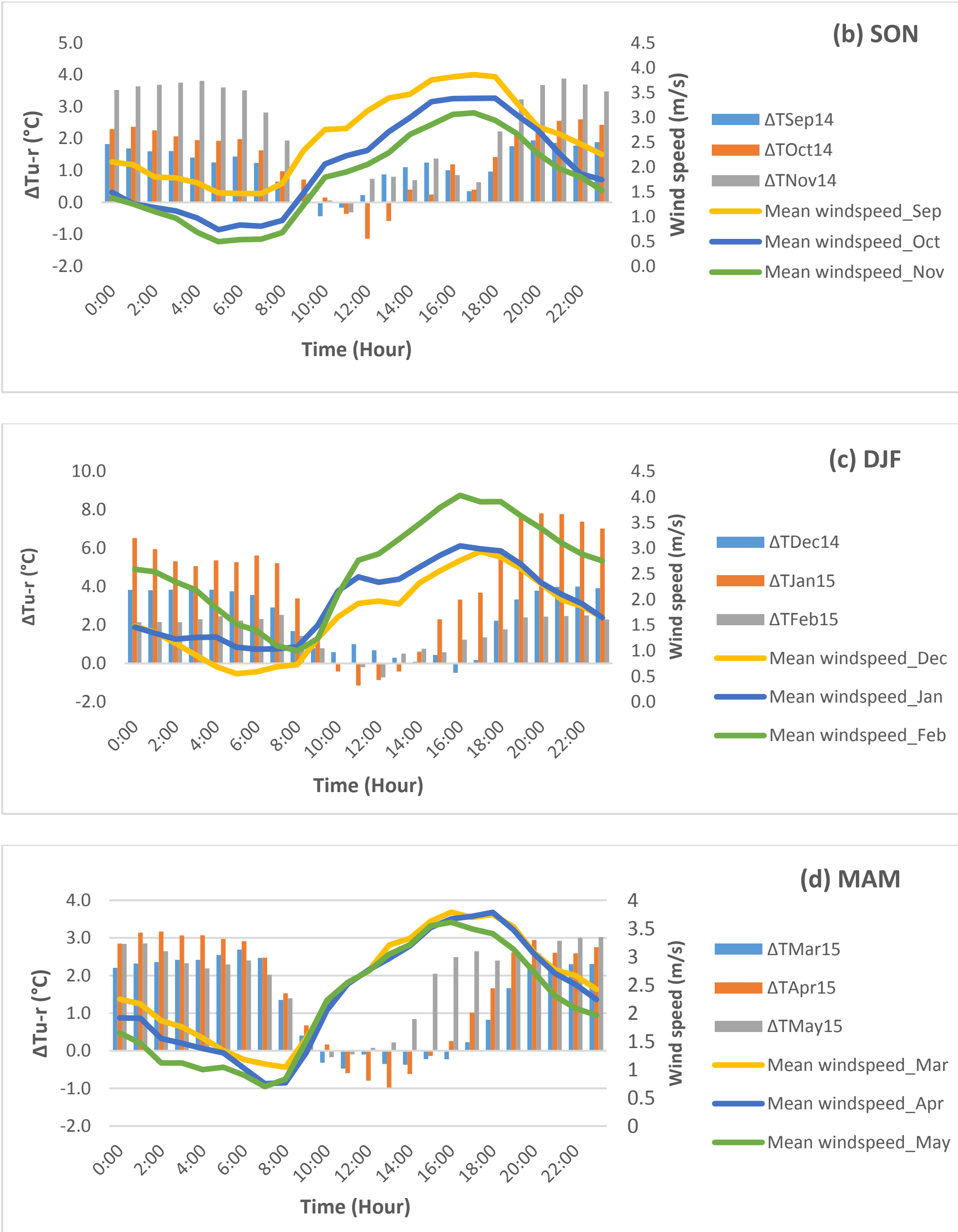


Figure 9. The effect of wind speed on UHI pattern in (**a**) JJA; (**b**) SON; (**c**) DJF and (**d**) MAM.

4. Conclusions and Recommendations

The urban-rural temperature differences, their variation in seasons as well as the effects of solar radiation and wind speed for Lagos have been investigated and discussed. Salient findings of the study are: (1) this study is one of very few to investigate urban temperature conditions in Lagos, the largest city in Africa and one of the most rapidly urbanizing megacities in the world; (2) maximum nocturnal UHI magnitudes in Lagos can exceed 7 °C during the dry season; and (3) during the rainy season, wet soils in the rural environment supersede regional wind speed as the dominant control over UHI magnitude. Projections of climate change suggest that Lagos State will experience a temperature rise of about 3 °C by 2100 [50]. We suggest that the effects of the heat island in Lagos on the thermal comfort, energy demand and health of its inhabitants should be considered as a study in the future but attention is drawn to the existence of the phenomenon in Lagos and possible reasons for its occurrence.

The implication of the study result is that policy towards making the city of Lagos less warm should be in place as the chances of mortality through heat stress especially among vulnerable populations are to be expected. Climate-smart urban planning is recommended with decentralization of economic activities from the city core and maintenance of urban gardens/parks and vegetation, which could ameliorate the heat effect. Moreso, cool and green roofs as well as the use of energy-efficient appliances and equipment could help in Lagos. However, there is a need to further this study by investigating the role of land/sea breeze on the UHI intensity in different seasons in Lagos.

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Abbreviations

The following abbreviations are used in this manuscript:

UHI	Urban Heat Island
UCI	Urban cool island
JJA	June, July, August
SON	September October, November
DJF	December, January February
MAM	March, April, May

Appendix

Google Image of Sensor Locations (the Red Points are the Sensor Locations)

Figure A1. Okoafo.

Figure A2. City hall.

Figure A3. Oshodi.

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