



Cooling rates and energy demand potentials of urban heat island in Akure, Nigeria

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ABSTRACT: This study was carried out to examine air temperature cooling rates and energy demand potentials of the Urban Heat Island (UHI) in Akure, a medium sized hot-humid tropical city in Nigeria. Investigations were conducted on the air temperature data obtained from a year-long (January to December 2010) simultaneous experiment of fixed point observations at the urban city centre and a rural reference site. The UHI which usually causes significant thermal alteration has been established from the climatological analysis of the differences in hourly air temperature between the two sites, using the most common UHI intensity index. The air temperature cooling rates and some energy demand parameters (cooling days and cooling degree hours) were also calculated and compared. Results showed that urban effect significantly reduced air temperature cooling rates over time, causing the rural site to cool relatively faster than the urban site. The energy demand parameters showed that high temperatures during the hot dry period at the onset of summer monsoon will enhance cooling energy demand in the city, thereby increasing loads on the electricity grid. At such time, the high UHI intensities will accelerate cooling load and enhance number of discomfort days with longer length of hours that requires cooling for comfort. However during the wet season, there is drastic reduction in the cooling energy demand due to the dominance of cloudy conditions during the daytime and cooling effect of the monsoon winds that are prevalent in the season, as well as pronounced decline in the nocturnal UHI intensities.

Key words: cooling rates, energy demand parameters, urban, rural.

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INTRODUCTION

It is well established that urbanisation has a significant effect on the local climate. The city of Akure has witnessed remarkable growth in its urbanisation in recent years, and its population during the past few decades has more than tripled (Balogun et al. 2011). Urbanisation has been reported to modify local city climates in most regions of the world. The resulting UHI is the characteristic warmth of urban areas compared to their outskirts. It is also often referred to as the increase of air temperature in the near-surface layer of the atmosphere within

cities relative to their surrounding countryside (Voogt, 2002).

The growth and intensity of the heat island depends upon the cooling rates of urban and rural environments. The markedly different thermal properties of the surfaces make the rates of cooling of urban and rural environs differ widely and growth of the heat island intensity varies with time of the night (Oke 1989). Several other authors have confirmed these results on urban-rural cooling rates (Eliasson 1994; Upmanis et al. 1998; Haeger-Eugensson and

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Holmer 1999; Tumanov et al. 1999; Runalls and Oke 2000, Holmer et al. 2007). However, these studies were carried out in mid- latitude cities. Weather has been identified to have significant impact on different sectors of the economy. One of the most sensitive is the electricity market, because power demand is linked to several weather variables, mainly to the air temperature. It has been well documented that weather-related factors play an important role in affecting electricity consumption. For many years, utility companies and the electric power industry have been interested in the relation between energy consumption and climate, and have developed empirical weather normalization algorithms aimed at improving load forecasting subject to variations in regional climate (Sailor, 2003). Most of the researches have been carried out by investigating the effect of increased air temperature in urban areas on energy demand of buildings (Graves, 2001; Kolokotroni, 2007; Asimakopoulos et al. 2001; Shahmohamadi, 2010). Some incorporated climate parameters in their models in the estimation of electricity demand (Alberini and Filippini, 2011; Psiloglou et al. 2009; Labandeira et al. 2011). In Spain, new empirical evidence using aggregated data on residential electricity was established (Blázquez, et al. 2012). Several other researchers have published estimates of climatic influences on energy consumption. Many publications focuses on energy consumption at the level of the individual residential or commercial buildings under idealized conditions (Scott et al. 1994; Huang, 1986) estimated the effects of climatic change on several prototype buildings and found a significant impact of weather variations on the energy consumption of individual buildings. Segal et al. (1992) investigated the role of climate parameters on peak electricity demand. The study was noted for analysing peak energy consumption and estimating possible implication for future generation capacity

requirements alongside its significant national policy implications. Robert et al. (1980) in Asheville, North Carolina showed that site specific energy and heating oil consumption for individual residences show a very high correlation with their National Weather Service's data when transformed into heating degree days. The degree day indicators are widely used in weather derivatives, energy trading, and weather risk management in the United States. A degree-day compares the outdoor temperature to a standard base value in degrees centigrade (°C); the more extreme the temperature, the higher the degree-day number. Thus, degree-day measurements can be used to describe the effect of outdoor temperature on the amount of energy needed for space heating or cooling. Degree-day statistics and techniques involving key weather parameters have proved useful in the assessment of heating and cooling requirements and the modeling of the impact of weather on national electricity demand.

Much of these research and related issues have been well investigated in the mid-latitudes but the knowledge gap is yet to be filled in some tropical countries such as Nigeria. Few works have been done on heat island intensities and humidity properties (Adebayo, 1991; Balogun et al. 2009) in the region. There are quite some limitations in relating energy load in terms of its distribution and consumption to weather parameters and resulting phenomenon such as the urban heat island in the country as data required for this kind of inspection are not available. However, we tried to assess the diurnal and seasonal magnitude of the heat island intensity and the degree day concept to establish the possible period of higher energy demands in the city and to what extent.

This work aims to relate the urbanisation induced heat island to energy demand potentials by using associated cooling rates and the degree day parameters to estimate the potentials.

DATA AND METHODOLOGY

The urban centre and the rural reference sites air temperatures were measured with portable Lascar EL-USB-2 temperature/humidity data loggers from January 2010 – December 2010. The device has an accuracy of +/- 0.5 °C. The loggers were programmed to sample at 5 minute intervals, sheltered with radiation shields and mounted on a lamp post above head height (3 m) in the city centre classified as Built Climate Zone 5 (BCZ 5), and on a mast at same height in the rural reference site (seldom use local Airport) located about 15 km east on the outskirts of the city, classified as Agricultural Climate Zone 3 (ACZ 3). The location of the ACZ 3 station (Observatory of the Nigerian Meteorological Agency) is nearly free from urban modifying effects. The two sites considered for this work were carefully selected and appropriated based on the urban rural classification scheme presented by Stewart, (2009). Position of the sensor at the urban site was carefully selected to prevent elevated heat sources such as rooftops.

The Hemispherical images are taken using a digital camera (Nikon Coolpix 950 with a 183-degree field of view fisheye lens) and the Sky View Factor (SVF) was calculated from the hemispherical images using a method outlined by Chapman et al. (2001). Figure 1 shows clearly the location and position of the measuring sites and sensors respectively.

The difference in temperatures between the city and the out-of-town stations, Tu-Tr, is the most commonly used index of the intensity of the UHI. In this paper the quantity of this difference is accepted as a measure of the city’s influence on thermal conditions. The urban heat island (UHI) intensities are obtained using the expression;

$$UHI = T_{urban} - T_{rural} \dots\dots\dots(1.0)$$

where *T* is air temperature,

The Cooling and Warming rates of both sites which influences the urban heat island intensity is calculated using;

$$\frac{\Delta T}{\Delta t} \dots\dots\dots(2.0)$$

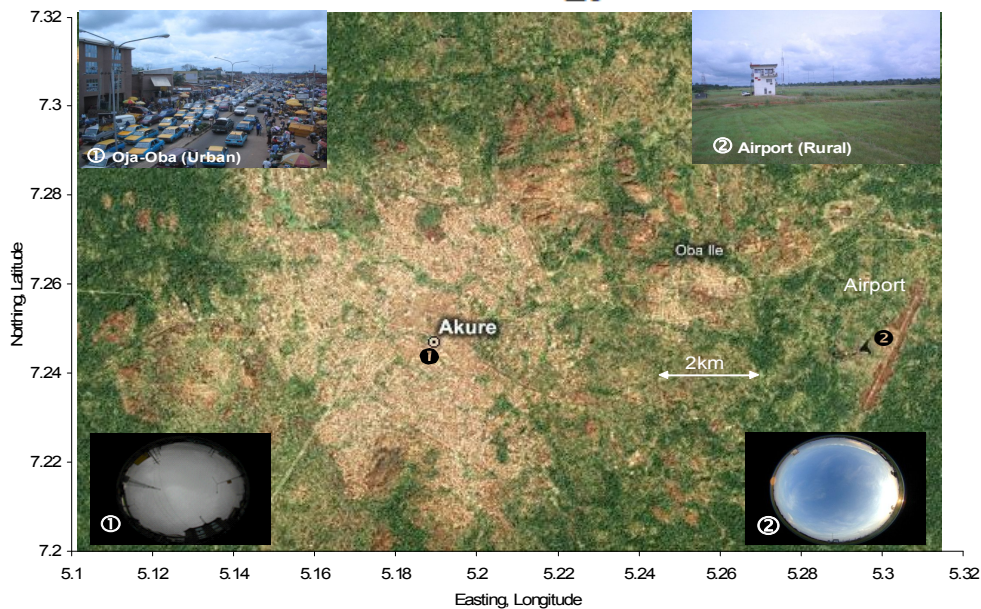


Fig. 1: Google map of Akure showing the study sites; city centre- BCZ 5 as (1) and rural reference site ACZ 3 as (2), with their eye level pictures and sky view photos (inset).

where T is the air temperature and t is time. To quantify the potential energy demand parameters at the sites, cooling degree days (CDD) values are compiled to assess how much energy may be needed in cooling for inhabitants comfort. Average temperature value is calculated for each day. If it is greater than the standard base, the standard base value is subtracted from calculated average temperature to yield the CDD. This is compiled for daily and totaled for entire month. The Cooling degree-days are calculated by the following formula;

$$CDD = \sum (T_i - T_b), \text{ if } T_i > T_b \dots \dots \dots (3.0)$$

where the base temperature (T_b) is taken as the required room air temperature (25°C).

Cooling days (CD) value are compiled at the sites to identify the number of days that requires cooling at the sites

$$CD = \sum (T_i > T_b) \dots \dots \dots (4.0)$$

where T_i is the daily mean temperature, T_b is set at 27°C for tropical environment.

RESULTS AND DISCUSSION

Average Air Temperatures at the Urban and Rural sites

The diurnal average of air temperatures measured at the urban and rural sites is presented in Figure 2. On the average, it is observed that the urban centre is constantly warmer than the rural reference site for all days of the months in the year under investigation. The marked difference reaching up to 2°C is noticed to occur from around sunset throughout the nighttime period until around sunrise the previous day. During the daytime, at few hours after sunrise, the differences become minimal till around sunset. The differences obtained can be

attributed to the peculiar surface and other characteristics of the urban environment as a result of urbanisation. The urban geometry, urban morphology, street canyons, albedo of urban surfaces, anthropogenic heat, vertical surfaces and the sky view factors (SVF) among others have been identified to be responsible for urban rural differences in air temperature. The SVF obtained from the sky view images of the urban and rural sites are 0.83 and 0.96 respectively. The sky-view factor is a dimensionless parameterisation of the quantity of visible sky at a location. Represented as a value between zero and one, SVF will approach

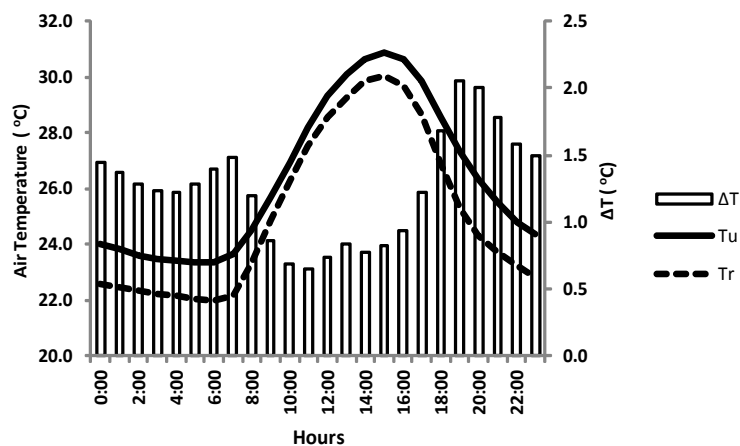


Fig 2: Diurnal variation of the mean air temperature at the urban (Tu) and rural (Tr) sites with the corresponding differences (ΔT) during the one year period.

unity in perfectly flat and open terrain, whereas locations with obstructions such as buildings and trees will cause SVF to become proportionally less (Oke, 1992).

Urban Heat Island (UHI)

The resulting heat island is subsequently established from the difference in these air temperatures as presented in Figure 3. Result revealed that the urban area is at all time warmer than the rural area thus, indicating the existence of urban heat island in Akure. The UHI is observed to occur throughout the day except for few days in December that urban cool island (UCI) is observed for just few hours in the afternoon. At this time, there is a reversed thermal contrast indicating a cooler city than its rural surrounding. This scenario has been observed to be attributed to extensive shading by tall buildings or other structures and a consequential lag in warming due to storage of heat by building materials. Similar result has been reported for Barcelona (Moreno-Garcia, 1994); Dallas (Ludwig, 1968) and Voogt (2004). The UCI occurs during the harmattan period that is usually associated with this part of the world. The heat island intensity is identified to be more of nocturnal phenomena as it is observed to be generally weak during the day in all the months

but with varying disparities in the strength of its weakness as shown in figure 3. During the nighttime when the weather condition is cloudless and windless, the heat island intensifies reaching the maximum that lingers through the nocturnal hours till around the time of sunrise. It is clearly shown in the Figure 3 that the highest UHI intensity occurs at night around 2100 - 2200 hours reaching 3.5°C in January, during the dry season. The strength of the heat island intensity is observed to be seasonally dependent as the intensity is observed to be highest in the dry months having its peak in the month of January. Results of most studies on UHI in the mid-latitudes reported UHI as an ephemeral phenomenon that occurs at night and vanishes during the daytime. In this tropical environment, the UHI exists throughout the day in all months of the year except the few hours of some days identified in late December, during the short winter-like harmattan period experienced in the city. The urban heat island characteristics and its seasonality have been extensively discussed in Balogun et al. 2012. The development of the urban heat island has certain influence on the duration of the cooling period and the quantity of cooling energy consumption.

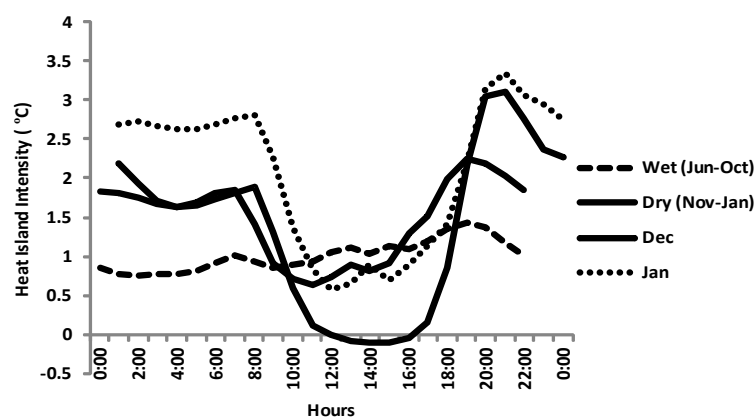


Fig 3: Diurnal variation of urban heat island intensities during wet and dry months, month with highest UHI intensity (January) and the only month indicating cool island (December)

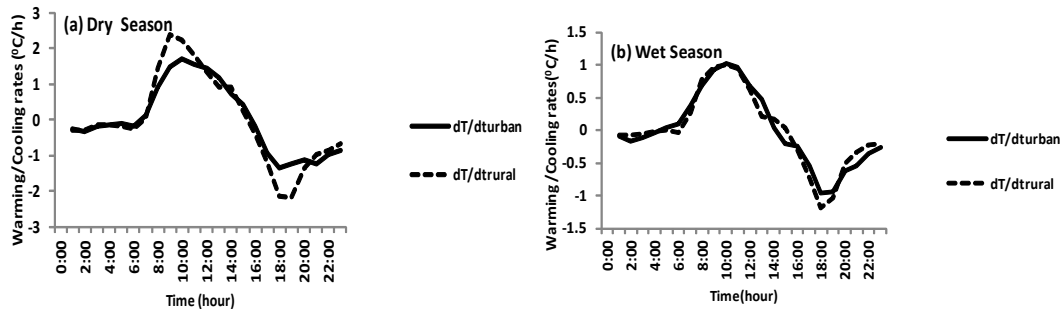


Fig.4. Diurnal warming and cooling rates during dry and wet season at the urban and rural sites

Cooling Rates and Energy demand Parameters

In this study, urban heat island has been identified to primarily result from differential cooling rates. Results have also revealed that the heat island increases the number of cooling days (CD) and cooling degree days (CDD). This will however increase the duration of periods that require cooling with consequential increase in the quantity of energy demand for the cooling and energy consumption rate in the urban centre when compared to that of the rural reference environment. For required human thermal comfort, there is a need of space cooling below a critical temperature level. The more extreme the condition, the more energy is consumed. Similar works have shown that the heat island effect presents a serious impact on electrical energy consumption especially for air conditioning (Taha, 1997, Santamouris, 2001). The numbers of cooling and heating degree hours can be used as index for defining ‘urban’ and ‘suburban’ places instead of the air temperature (Livada et al., 2002). It is also observed that the number of the cooling days is a simpler approach to the climate differences whereas cooling degree-days and hours reflect the amount of cooling energy demand as a function of the mean daily temperature. Similar

observation was reported for Szeged, Hungary by Unger and Makra, 2007.

Cooling Rates

These inhomogeneous warming and cooling rates in the urban centre and the rural site with their effect on the Urban Heat Island (UHI) in Akure were investigated. Figure 4 presents the observed warming and cooling rates at the urban and the rural sites for both the dry and wet seasons of the year. During the dry season, assessment of the temporal development of the warming and cooling observed at the sites showed that the rural site warms and cools faster than the urban site. It also indicated that warming and cooling rates are markedly different between the sites on hourly basis at few hours after sunrise and from sunset to about 5 hours thereafter. The atmospheric urban heat island is observed to primarily result from differential cooling rates. The UHI intensity has been identified to be highest at nighttime in the dry season, occurring at about 1-2 hour time lag of sharp contrast in urban- rural cooling rates.

Cooling Days

The comparison of the monthly means of urban and rural cooling days (CDs) is presented in

Figure 5. Monthly means of cooling days in the urban centre exceeded those of the rural area except for the months of July through September during the summer monsoon. Apart from this period, the minimum and maximum differences are between 4 and 21 days in September and January respectively. The month of March is observed to have the highest peak of days that requires cooling at both sites, with the total number of days in the month exceeding threshold at the urban centre. The figure shows that the cooling season begins around November and lasts till June at the urban centre

having as much as 25 days and above that will require additional cooling to achieve human thermal comfort. The situation is quite different at the rural station as the cooling days were observed to be predominantly significant in March. Consequently, the overall assessment revealed that the period that requires additional cooling in the rural station is about 15 weeks shorter than that of the urban centre for the one year under study. Our observations are quite similar to earlier reports on the temporal developments of the cooling rates in mid latitude cities (Oke and Maxwell, 1975; Oke, 1982).

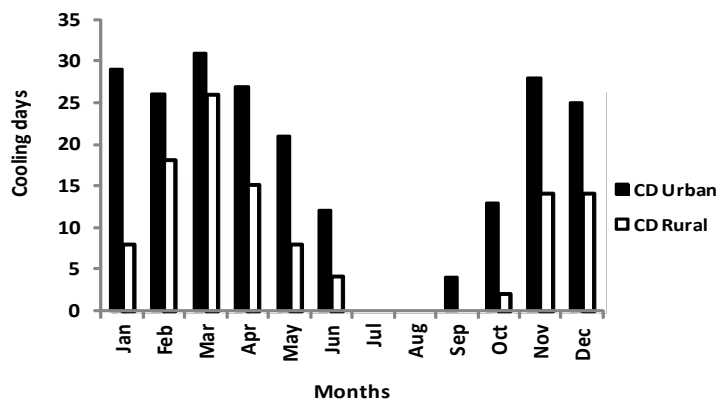


Fig 5: Monthly variation of the cooling days at the urban centre and the rural reference site

Cooling Degree Days

Degree days are a specialised type of weather data, calculated from readings of outside air temperature, used extensively in calculations relating to building or space energy consumption. Figure 6 shows the monthly mean numbers of the cooling degree days calculated for the urban and rural sites under investigation. The cooling degree day (CDD) is a clearer measure for the comparison of the cooling energy consumption. The cooling season as identified from the results of the cooling days, is characterized by significant cooling demand which lasts several months in the city than the airport site. The cooling degree days for all the

months were at all time higher at the urban city site than recorded for the rural site. The highest cooling energy demand obtained occurs in the month of March at both sites. The most significant difference in CDD appears in January (about 64 °C higher in the urban than the rural site). Consequently, the urbanisation influence of the city centre on cooling energy demand is stronger at the dry season. The calculated CDD values obtained are positive at all time of the year except during the summer monsoon, in which negative values were recorded in August at the urban centre and from June to September at the rural station. During these months, the summer monsoon has fully developed, resulting

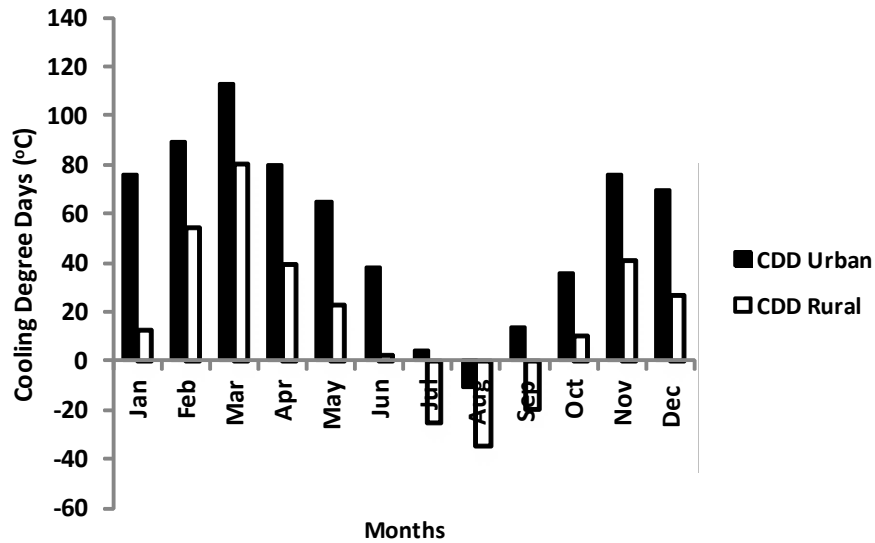


Fig 6. Monthly variation of the cooling degree days at the urban centre and the rural reference sites

in reduced cooling demand due to cooling effect of monsoon winds and overcast cloud conditions. CDD values were very low and falls below its threshold at both sites, suggesting observed situation at the rural site to be typical of space heating rather than cooling, however the extent at which the base temperature is higher than the measured was not significant enough to heating demand. Balogun et al., 2012

identified and reported this period to exhibit daytime and nighttime heat island intensities that are almost of the same magnitude.

Cooling Degree Hours

The cooling degree hours (CDHr) calculated for the period of study is presented in Table 1. The summation of average cooling degree hours (°C) for each day in individual months were presented

Table 1: Observed daily average of cooling demand hours, cooling degree hours (CDHr) and the time (hour) that cooling demand usually begins at both urban and the rural stations

Months	Urban Area			Rural Area		
	Daily Ave. of Hours	CDHr (° C)	Cooling Demand Begins at	Daily Ave. of Hours	CDHr (° C)	Cooling Demand Begins at
Jan	14	68	9am	10	48	10am
Feb	15	77	8am	12	59	9am
Mar	20	87	8am	13	66	9am
Apr	15	71	9am	12	50	10am
May	14	56	8am	11	39	9am
Jun	12	42	9am	9	27	10am
Jul	9	22	10am	7	13	11am
Aug	8	17	11am	6	10	12noon
Sept	10	30	10am	7	16	11am
Oct	11	46	9am	10	38	10am
Nov	13	54	9am	11	55	10am
Dec	14	64	9am	11	52	10am

in the table for both sites. It is clearly shown that the obtained values of average amount of hours that requires cooling and the consequential amount of degree centigrade that is needed to be cooled in achieving inhabitants thermal comfort were in all the months higher at the urban area. A one-hour time lag in period of the day that cooling demand begins between the urban and rural site was observed in this study. In agreement with the results of the cooling day and cooling degree days, the cooling degree hour for the wet season also indicated that there is reduction in cooling energy demand during the wet season as the obtained values alongside the average number of hours per day were considerably smaller than those obtained during the dry season at both sites. However, the urban effect is still noticeable as values are higher at the urban centre.

Figure 7 presents the relationship between the UHI and cooling degree hour estimated for both the urban centre and the rural reference site. The marked difference in cooling demand in

terms of cooling degree hours is clearly shown in this figure. The cooling degree hour is at all times of the day higher at the urban centre as compared to the rural site. Just like the average diurnal pattern of air temperature, Both the city and the rural sites cooling degree hour increases rapidly after the sunrise and gradually decreases after sunset. The degree of the demand is observed to increase diurnally relative to the air temperature pattern and having its peak around 1600hrs. The magnitude of the heat island is directly related to the degree of the hourly cooling demand. During the daytime, the UHI intensities are lower and having a corresponding little difference in the cooling demand between both urban and rural sites. But the higher nocturnal UHI intensities are observed when there are marked difference in the cooling degree hours of the urban centre and the rural sites. The marked difference usually begins about two hours after sunset and maintains its course throughout the night till around the sunset the following day.

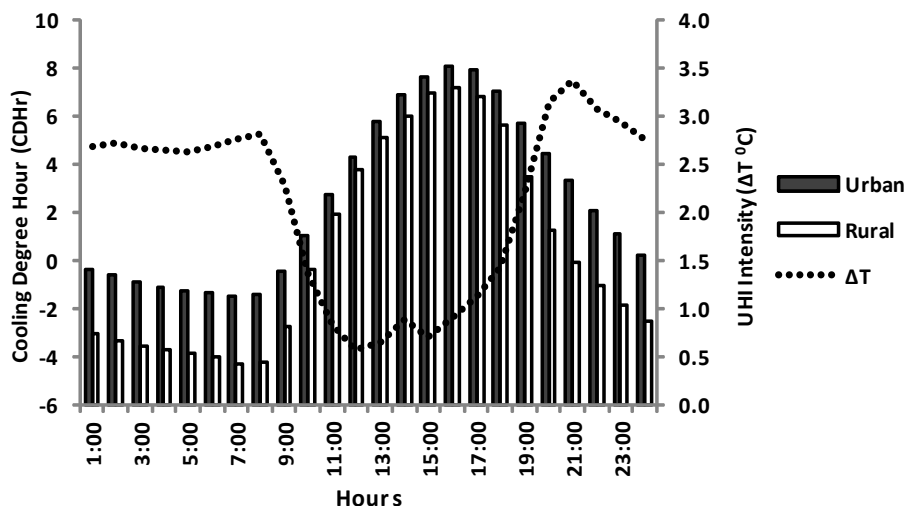


Fig. 7: Diurnal variation of the cooling degree hour (CDHr) obtained from the urban and rural sites with the heat island intensity (UHI)

CONCLUSION

That the rapid growth of a city has a profound impact on the quality of the thermal environment and air has been confirmed in many temperate countries, but studies are relatively lacking in the low tropics. This study examined air temperature cooling rates and the potential impact of the resultant urban heat islands (UHI) on the energy consumption and demand for space cooling by comparing an urban and a rural site in Akure. The study utilizes the degree day concept in obtaining its objectives. Results have revealed interesting findings and supports previous research on impact of UHI on energy demand and consumption. Urban effect significantly reduced cooling rates over time as the rural site warms and cools relatively faster than the urban site. The climate modifying effect of the urban heat island in a medium-sized hot humid tropical city causes significant thermal alterations as revealed by our simple measures. The UHI has been found to occur throughout the day and night except for a few hours after noon in November and December where a cool Island is observed. The heat island intensity is also noted to be generally weak during the day

in all the season but with varying disparities. However, the highest UHI intensity occurs at night between 1800 to 2200 hours and the intensity is also higher in the dry than the wet seasons.

Cooling days, Cooling Degree Days and Cooling degree hours in the urban area have been confirmed to exceed those of the rural area. All these parameters have established the effect of the urbanisation on the cooling energy demand as it is stronger at the urban area than the rural site in all season. The elevation of temperature (urban heat islands) in the urban areas at both day and night increases the potential for cooling to give inhabitants the required comfort. These has been revealed in the results indicating increasing number of cooling days, cooling degree days and the cooling degree hour, This may therefore lead to increased use of fans and air-conditioning, hence adding more pressure to the electricity grid during peak periods of demand. It may also leads to deteriorating of the climate and air quality by the extensive use of power generators at such periods.

RECOMMENDATIONS

The long term problems facing the energy sector of the country has made it difficult to provide required information and data on energy provision and consumption which are essential in most climatological related researches that can assist in assessing costs and providing guidance in fostering sustainable policies in the sector. By studying degree-day patterns, it is possible to evaluate the increases or decreases in costs associated with heating or cooling bills from year to year. It is important to note that there will not be a direct correlation between the percentage increase / decrease in heating or cooling degree days and the percentage increase in the customer's energy bill, but the

degree day data will provide an indicator that the increase / decrease in the temperature will result in an increase / decrease in the need for cooling.

However, there is need to introduce and encourage urban heat island mitigation measures that will not induce increasing energy consumption, particularly at the face of the changing climate. Part of the measures to be introduced include building climate resilient cities through encouragement of climate adapted architecture, ensuring urban greening, tree planting programmes and blue roof technologies.

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