Assessment of Urban Heat Island and Energy Demand Parameters in Akure, Nigeria.

*I. A. Balogun, A. A. Balogun, Z. D Adeyewa
Department of Meteorology,
Federal University of Technology,
PMB 704, Akure 340001,
Nigeria

CORRESPONDING AUTHOR
I.A Balogun
Department of Meteorology,
Federal University of Technology,
PMB 704, Akure 340001,
Nigeria
E-mail- iabalogun@futa.edu.ng
Phone no- +234-803-919-4212

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ABSTRACT

It is well known that urbanisation has a significant effect on the local climate; thereby causing the climate of an urban area to differ from that of a nearby rural area. This paper investigates the climate modifying effect of urban growth in Akure, a medium-sized rapid developing south western city in Nigeria which lies in the tropics, and this is noted to have caused significant thermal alterations which are revealed by a year-long in situ measurement and analysis as presented in this work. The paper also attempts to establish the role of the urban heat island on energy demand by assessing the differences in degree day parameters between the urban city centre and the rural reference airport site. Results showed that the elevated temperatures during the dry period, particularly at the onset of summer monsoon in the city increases energy demand for cooling which is capable of adding pressure to the electricity grid during peak periods of demand. In this period, the increasing intensity of the Urban Heat Island (UHI) will tend to result in an increased cooling load and an increased number of human discomfort days as revealed by longer length of hours that required cooling. But when the summer monsoon has fully developed, the lowered UHI intensity will tend to result in reduced cooling demand due to cooling effect of monsoon winds.

Key words: Urban heat island, cooling degree day, energy demand.

1. Introduction

The modification of the natural surface, release of artificial energy and polluting materials into the atmosphere over the cities alter radiation and energy balance in urban environments. This as a result produces a peculiar local climate, termed the ‘urban climate’. The most obvious manifestation and best documented example of this inadvertent climate modification is the urban heat island Oke, 1987. This means that warmer areas appear within settlements as compared to the surroundings. Urban areas have significant heat storage and thermal inertia from this process is believed to be instrumental in creation of the urban heat island effect, Grimmond and Oke, 1999b. The heat excess has lots of practical consequences, which may influence everyday life. Weather has a 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 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, 2001). Much research has been carried out investigating the effect of increased air temperature in urban areas on energy demand of buildings (Chandler, 1965; Graves et al, 2001; Kolokotroni et al, 2006). Several researchers have published estimates of climatic influences on energy consumption. Many of the publications in this area, however, focus on energy consumption at the level of the individual residential or commercial building under idealized conditions. For example, Scott et al, 1994 estimated the effects of climatic change on several prototype commercial buildings in various US cities. Huang et al, 1986 conducted a similar climate sensitivity study using the DoE-2 building energy simulation code to simulate both residential and commercial buildings. Both authors found a significant impact of weather variations on the energy consumption of individual buildings.

There are limited studies done at regional scale level. One of such is the work of Segal et al, 1992 that investigated the role of climate parameters in affecting the peak demand in Israel. The significance of the study was noted as it analyses peak energy consumption and was able to estimate possible implication for future generation capacity requirements and its significant national policy implications as its spatial domain was an entire country. Valour et al, (2001) analyzes the relationship between electricity load and daily air temperature in Spain, using a population-weighted temperature index and part of their results having isolated weather influence on electricity loads from socioeconomic factors, revealed that the sensitivity of electricity load to daily air temperature has increased along time, in a higher degree for summer than for winter. Robert et al (1980-) in his work on Asheville, North Carolina showed that site specific energy and heating oil consumption for individual residences show a very high correlation with their National Weather Services data when transformed into heating degree days. In the United States, for example, degree day indicators are widely used in weather derivatives, energy trading, and weather risk management.

However, much of these research and related issues has been investigated in the mid-latitudes but few works done focused on characteristics of the heat island intensities and humidity properties (Adebayo, 1987; Adebayo, 1991 and Balogun et al. 2009a and Balogun et al 2009b & c). This work is a pioneering research in the country trying to relate the urban heat Island and its associated degree day parameters to energy demand. There are quite some limitations in directly relating energy load in terms of its distribution and consumption to the urban heat island in the country as data required for this kind of inspection are not available. Hence, is difficult to furnish us with needed information. However, we attempt to assess the diurnal and seasonal magnitude of the heat island intensity and the degree day concept at an urban and a rural site, and also establish the possible period of higher energy demands in the city.

2. Study Area and Measurement Sites

Akure, the capital city of Ondo State, Nigeria is located on latitude 7°25’N and longitude 5°20’E (Fig 1). The rapid growth of the city, particularly within the last 25 years, has made it one of the fastest growing metropolitan areas in the Southwestern Nigeria. Its population has more than tripled from 157 947 in 1990 to ~500 000 in 2006. It became an administrative and economic seat to Akure South Local Government Authority, and Ondo State with the latter’s creation in 1976 from the old Western Region. Since then, the city has witnessed immense growth in the size of built-up areas, number of immigrants, transportation, and commercial activities. It experiences warm humid tropical climate, with average rainfall of about 1500mm per annum. Annual average temperatures range between 21.4 and 31.1°C, and its mean annual relative humidity is about 77.1% (based on 1980-2007 data from the Nigerian Meteorological Agency). Its vegetation is the tropical rainforest type. Akure lies on a relatively flat plain of about 360m above sea level within the Western Nigerian plains.
Fig 1. Location Map of Nigeria showing the study area, Akure

The urban site is located at the city centre characterized by dense population, intense transportation and commercial activity. The rural reference site is situated at the meteorological service observatory of the seldom used local airport located about 15 km east on the outskirt of the city, nearly free from urban modifying effects as it is characterized by massive grass-covered open plots, few bungalow office buildings and the control tower. Figure 2 shows the study sites with the eye level photos and sky view features of both the urban and rural stations. Issues pertaining to discrepancies in the classification of urban–rural measurement sites for defining urban heat island has been reported by Stewart, 2009 and its highlight on the universally applicable scheme have been taken into consideration in this work. Hence, the city centre having a sky view factor of 0.73 is classified as Built Climate Zone 5 (BCZ 5) and the airport which has a sky view factor of 0.98, classified as Agricultural Climate Zone 3 (ACZ 3).
3. Data and Methods

A year-long in-situ simultaneous measurement of air temperatures were carried out at the urban city centre and the rural reference airport using portable Lascar EL-USB-2 temperature/humidity data loggers. 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 and on a mast at same height in the local airport.

The urban heat island denoted by $\Delta T_{u-r}$, is the difference in air temperature between the urban and rural site

$$\text{UHI} = T_{\text{Urban}} - T_{\text{Rural}}$$

where $T$ is air temperature.

It 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 number of cooling days (CD) is defined as the number of days that daily mean temperature ($t_i$) is above or equals a critical value of 27°C. Cooling degree days are values complied daily to assess how much energy may be needed in cooling buildings for inhabitants comfort. In determining CDD, average temperature value is calculated for a given 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 (CDD) are calculated by the following formula;

$$\text{CDDs} = \sum (t_i - T_b), \text{ if } t_i > T_b$$

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

The rationale behind this technique is that whenever average temperature drops or exceeds the comfort range, some heating / cooling will be required, the requirement for heating increases with decreasing temperature and vice versa. The Cooling degree-day is a more exact measure for the comparison of the cooling energy consumption.
4. Results and Discussion

4.1 Urban Heat Island

The urban heat island has been established to occur in Akure. The result regarding the urban rural air temperature differences $\Delta T_{u-r}$ at both sites is presented in Fig 3. It shows that the UHI exists in Akure throughout the day except in November and December where urban cool island (UCI) is observed for few hours in the afternoon in both months. Daytime heat islands may be positive or negative depending on the particular characteristics of the urban area and their surroundings. Highest UHI values observed in the dry season agrees with Balogun et al, 2009a that reported UCI at 1500 in October/November and higher UHI values in January/February in Akure. However, results from this study slightly differ as the higher UHI values are observed in November through January but with January recording the highest value in overall. During the wet season, the UHI formed at night is preserved and almost unchanged throughout the day but during the dry season; the UHI formed at night is preserved until the morning hours and significantly drops in intensity or completely vanishes during midday. Annual course of the UHI at the time of the morning observation depends more on the time of sunrise relative to the time of observation, than on any factual dynamics of the weather conditions. The maximum UHI occurs at night between 1800 and 2200 local time having its peak around 2100. The peak period, on the average, might be linked to the release of sensible heat from "rush hour traffic" occurring in the city as a result of closing hours and evening market transactions from about 1800- 2100 thereabout. Thereafter, the heat island continues to develop through the early morning hours due mainly to the rural net radiative energy loss to an unobstructed sky and less polluted atmosphere prior to sunrise. After this time, the solar heating generates a turbulent mixed layer over both the urban surfaces and the city environs, so thermal contrasts decline until around the end of the afternoon.

![Fig 3. Diurnal variation of mean monthly urban – rural differences of air temperature](image)

The observed heat island, particularly at the periods of high intensities has the potency of increasing the number of cooling days, cooling degree days and the cooling degree hour, as it will however increases the duration of periods that requires additional cooling to give inhabitants the required comfort. This will however increase the quantity of energy demand and enhances electricity consumption rate in the city. For human comfort, there is a need of space cooling below a critical temperature level. The more extreme the condition, the more energy is consumed.
4.2 Cooling Days

The comparison of the monthly means of urban and rural cooling days (CDs) as shown in Fig 4 indicates that the cooling season begins in November and lasts till around June in the urban centre site. The situation is quite different at the rural site as the cooling days were observed to predominantly occur between February and April. Except for the months of July and August, monthly means of cooling days in the urban area exceeded those of the rural area and the differences are between 4 and 21 days in September and January respectively. Consequently, our overall assessment revealed that the period that requires additional cooling in the rural station is more than 15 weeks shorter than experienced in the urban centre for the one year under study. Seasonally, the wet season has reduced cooling days than observed during the dry season and the transitional months which are the onset into the summer monsoon.

4.3 Cooling Degree Days

Figure 5 shows the monthly mean numbers of the cooling degree days calculate for the urban and rural sites under investigation. The cooling degree day 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 demand obtained occurs in the month of March at both sites. The most significant difference in CDDs appears in January (about 64°C higher in the urban than the rural site). Consequently, the effect of the city on the cooling energy demand is stronger than in other period of the cooling season.

The CDD values obtained are positive at all time of the year except for the month of august in the urban city and June to September at the rural airport. Although these months exhibits a generally low value of CDD at both sites, the rural airport shows totally different peculiarities as the situation were absolutely typical of space heating demand rather than cooling at the rural site. In this period, the summer monsoon has fully developed, resulting in reduced cooling demand due to cooling effect of monsoon winds.
4.4 Cooling Degree Hours (CDHrs)

Table 1: Cooling degree hours (CHr) and the time cooling demand begins at both urban (city) and the rural (airport) stations.

<table>
<thead>
<tr>
<th>Months</th>
<th>CDHr City</th>
<th></th>
<th></th>
<th>CDHr Airport</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>Hrs</td>
<td>Deg</td>
<td>Cooling Demand Begins at</td>
<td>Hrs</td>
<td>Deg</td>
</tr>
<tr>
<td>Oct</td>
<td>11</td>
<td>46</td>
<td>9am</td>
<td>10</td>
<td>38</td>
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<tr>
<td>Nov</td>
<td>13</td>
<td>54</td>
<td>9am</td>
<td>11</td>
<td>55</td>
</tr>
<tr>
<td>Dec</td>
<td>14</td>
<td>64</td>
<td>9am</td>
<td>11</td>
<td>52</td>
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<tr>
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<td>68</td>
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<td>10</td>
<td>48</td>
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<td>8am</td>
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<td>16</td>
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</tbody>
</table>

Fig 5: Seasonal variation of the cooling degree days (CDDs) in the two sites (urban and rural)
The cooling degree hours calculated for the period of study (October 2008 to November 2009) is presented in Table 1 shown above. A one-hour time lag in period that additional cooling demand begins between the urban and rural site was observed. The urban site in the transitional months of February and March exhibits conditions that almost require cooling all day long. It is also observed that features that appear typical of heating demand also exists virtually in some nocturnal hours, particularly in the early morning from around 2300 to 0500hrs at both sites with the exemption of February and March in the urban city. The cool conditions that bring about the seemingly heating demand are more prevalent during the wet season, particularly in the months of intense rainfall during the monsoon. However, the early hours heating demand was noticed to be more intense in the rural site with the highest record in January in terms of intensity but highest in magnitude in August during the period of the little dry season.

Considering the relationship between the UHI and cooling degree hour as shown in Fig 6, the cooling demand is constantly higher at the city than the rural site at every hour of the day. 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 with its peak around 1600.

The intensity of the heat island is directly related to the differences in degree of the hourly cooling demand between the city centre and the rural airport site. The UHI intensity is lower during the day when there are little difference in the cooling demand between both urban and rural sites and the UHI intensity is observed to be higher in the early morning and late evening when the cooling demand differences are large.

5. Conclusion

This study establishes the existence and discusses characteristics of the urban heat island in Akure. It also compares the degree day parameters between the urban and rural site with a view of identifying the probable roles of the urban heat islands (UHI) on energy demand and consumption for space cooling in the city. Results have revealed interesting findings and supports previous research on impact of UHI on energy demand and consumption. 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 local time and having its peak around 2100. The intensities are also higher in the dry than the wet seasons. Cooling days in the urban area have been confirmed to exceed those of the rural area. The cooling degree day values have also shown that the effect of the city on the cooling energy demand is stronger than that of the rural site in every period of the year. The intensity of the heat island is directly related to the differences in degree of the hourly cooling demand between the city centre and the rural airport site. The result suggests that the total energy consumption in the urban city site will increase as the need for space cooling increases due to the effects of the heat island. This demand for cooling will definitely add pressure to the electricity grid during peak periods of demand.
There is need to introduce mitigation measures of UHI that will not induce increase energy consumption. Part of the measures may include ensuring urban greening by creating urban parks and trees. Mitigation measures that will be effective in at all season of the year should be given priority.

References


