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Article

Geospatial Modeling of Human Thermal Comfort in Akure Metropolis Using Thom's Discomfort Index

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Abstract: This study was carried out in Akure, the capital city of Ondo state, Nigeria. The city was divided into five (5) landuse classes (Administrative, Commercial, Industrial, Institutional and Residential). The study's objective was to determine the thermal comfort or discomfort of people to the environmental conditions that obtains particularly temperature and relative humidity in Akure, with respect to the thermal discomfort index (DI). This index was calculated from Thom's formula which is DI = T - (0.55-0.0055*RH) (T-14.5). The interested micro-climatic parameters of air temperature and relative humidity, were obtained from the archives of era interim (ECMWF) for a period of 31 years (1986-2017). Decadal averaging was done (using Microsoft Excel) on the discomfort index values obtained to break the discomfort values into three decades (1986 – 1996, 1997 – 2006, and 2007 – 2017). Thom's Table of DI Ranges was used to determine the percentage of the population of Akure metropolis suffering from discomfort or otherwise. From this study, it can be inferred that over a period of 31years, over 50% of the population in Akure are experiencing thermal discomfort. The discomfort indices greater than 30 or 32 (indicating 100% of the population feeling discomfort or the condition of medical emergency, respectively) were not attained in Akure metropolis over the same period of 31years.

Keywords: Discomfort Index, Thermal Comfort, Urban Heat, Akure Metropolis, Climate Change, Thom's Index.

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1. Introduction

Urban micro-climate tends to have a very important impact on the human thermal comfort of an urban environment. In a growing urban environment like Akure, the commonly prevalent high temperatures, especially during the dry season, that produces the urban heat island effect, also tend to aggravate the comfort/discomfort conditions of the city dwellers (Adegoke, 2018). The climate of the Earth has been established to vary across temporal and spatial scales. And with the ongoing climate change awareness, temperature is one of the major climatic variables that is mostly affected by global warming, climate variability and climate change as a whole. As a consequence, the frequency of humidity and temperature variability for many regions of the earth will increase. This effect can be seen on human well-being and the environment (Adekayi, 2009).

McPherson (1962), defined the following six factors as those affecting thermal sensation: four physical variables (air velocity, air temperature, relative humidity, and mean radiant temperature) and two personal variables (clothing insulation and activity level, i.e. metabolic rate). Ati (2002), defined temperature as the degree of sensible heat or cold within the atmosphere while relative humidity, as the ratio of the observed humidity mixing ratio to that which would saturate the air at the same temperature. In spite of the achievement of scientist through modern technology the comfort of human population is still influenced to a great extent by these two thermal indices: temperature and humidity.

Thermal comfort indices are diverse and usually applicable only in certain conditions, as defined by environmental ranges. This range of applicability is however only specified for some indices. Furthermore, analyses of these indices by ASHRAE (1981) and Fanger (1970) conclude that they are applicable in a much narrower range of environmental conditions than claimed. Many thermal indexes have been widely used to express the human comfort level on areas or time periods by the combination of meteorological and physiological data based on environmental conditions.

From records of previous studies and indices considered for Nigeria, it was suggested that temperature – humidity index (THI) is important as an index of thermal comfort in the tropics because it has the advantage of providing the combined effect of temperature and humidity on comfort within a narrow range of environmental conditions (Balogun *et al*, 2014). The index also has the capability of giving direct, rather predictive results of thermal comfort conditions relying only on temperature and humidity values. THI is also used to calculate human thermal conditions so as to assess the relationship between meteorological variables, such as air temperature and relative humidity. Thom (1959), showed that the effective temperature ET*, over a wide range of its values under outdoor conditions, could be approximated by a simple linear equation incorporating the physical parameters of air temperature (dry-bulb temperature) and the wet-bulb temperature. This proposed empirical index, which is in fact a variant of ET*, is what he called the temperature-humidity index (THI) or what is more generally known now

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as the discomfort index (DI). Researchers have proposed a number of rational or empirical bioclimatic indices that describe the sensation of warmth that a person experiences due to exposure to different combinations of parameters that influence thermal comfort such as air temperature, relative humidity, air velocity, barometric pressure, clothing, activity etc. The effective temperature index ET* was the first attempt in analyzing human comfort. This empirical index combines air temperature and humidity but depending besides on clothing and activity of a person, it is not possible to generate a universal ET* chart. In contrast to the effective temperature, the DI provides an easily evaluated measure describing the degree of discomfort at various combinations of temperature and humidity. Due to its simplicity, DI is probably the most common bioclimatic index and it is used extensively for many outdoor thermal comfort applications.

The bioclimatic index based on a simple empirical formula permits accurate evaluation and provides information about discomfort conditions at a site. Especially for a general evaluation of the comfort conditions in outdoor spaces, where the wind speed and the radiation is spatially variable, and more complex comfort indices cannot be used, the Thom's Discomfort index offers valuable and accurate information which is required for comfort and energy purposes.

Humans have always been aware that weather and climate affect their health and well being. But despite this awareness, there had not been much research work carried out in this area in our own part of the world as a country. Planners and policy makers should have firsthand information about the regions for which they are responsible. However, it seems that many developing countries, including Nigeria, are not adequately prepared either for their current climates or for the impact of climate change because they lack sufficient information. Knowledge of the thermal climate of Akure is therefore vital for planning on health, urban development, tourism and migration, among other matters. As Akure continues to witness rapid urbanization, two questions this work seeks to provide an answer for are:

i. What is the extent of variation in thermal comfort experienced across different landuse types in Akure?
ii. What is the relationship between the land surface temperature and the thermal comfort in Akure?

1.1. Study Area

The study area is Akure metropolis, the administrative capital of Ondo State. Akure became the state capital of Ondo State in 1976. It lies between longitude 5°06'E and latitude 7°37'N in the Southwestern Nigeria (Figure. 1.1). It cuts across both Akure South LGA and Akure North LGA with an area of approximately 991 square kilometers (Ibitoye*et al.*, 2017).The city has a population of 353,211 as at 2006 (Federal Bureau of Statistics, 2007) which would have grown to 474,686 by 2016, using the Nigeria Population Commission annual growth rate of 3% for urban centres in Nigeria. Akure and its environs experience a frequent annual rainfall of over 1500 mm with a short August break. The average

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temperature is about 22°C during harmattan (December-February) and 32°C in March. The vegetation is tropical rainforest and drained by River Ala and its tributaries (Adegoke, 2018). Characteristically, the wet season ranges between April and October, while the dry season ranges between November and March. Akure maintains a moderately warm humid tropical climate with high temperature. Maximum temperature of about 35^{0}C is usually recorded in March (Adegoke, 2018).

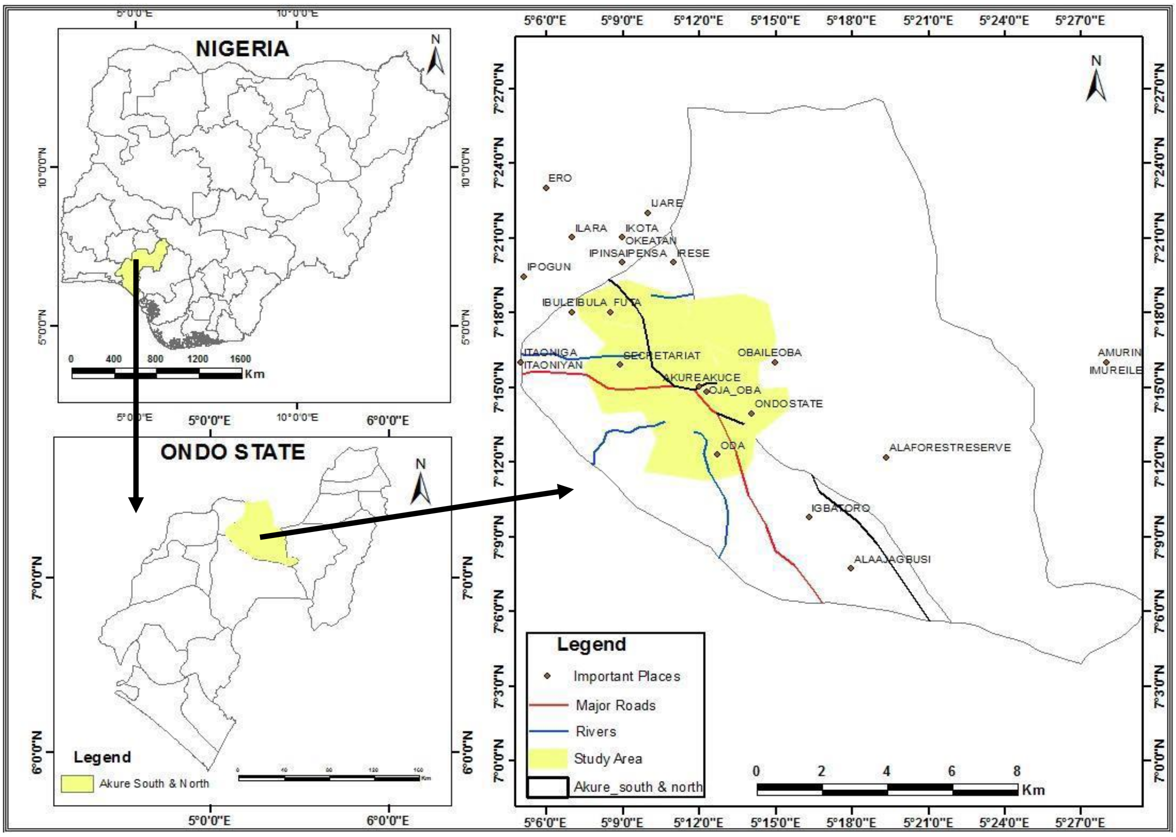

Figure 1: Location of study area

2. Materials and Methods

2.1. Materials

This study made use of secondary data. The secondary datasets include micro-climatic data (Air Temperature and Relative Humidity), LandSat Images (1986, 2002 and 2017) and georectified IKONOS satellite image (2017). The micro-climatic (temperature and relative humidity) data was retrieved from the archives of ECMWF (ERA INTERIM) for a period of 31years (1986 – 2017), while the LandSat images for three (3) different years (1986, 2002 and 2017) were obtained from the archives of the United States Geological Survey (USGS). The study area was divided into five different landuse areas. These landuse division include residential, commercial, administrative, institutional (tertiary) and industrial.

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2.2. Spatial Variation in Human Comfort

The interested micro-climatic parameters of air temperature and relative humidity, were obtained from the archives of era interim (ECMWF) for a period of 31 years. It is a gridded data with default grid of 0.75 x 0.75, which was resampled to the desired grid of 0.0125 x 0.0125 in order to get several points across the study area. A total of 12 (measurement) points were obtained within Akure metropolis cutting through the five landuse classes of Administrative (2 points), Commercial (2 points), Residential (5 points), Industrial (1 point) and Tertiary (2 points).

The discomfort index (DI) is a popular and useful bioclimatic index that had been in use for over 4 decades in the study of thermal comfort. The Discomfort Index by Thom (1959) was adopted for this study based on its appropriateness for tropical climate and its simplicity (Eludoyin, 2013). Thom's discomfort index (DI) is expressed by a simple linear equation based on dry-bulb (Tdry) and wet-bulb (Twet) temperatures. Its original form was:

$$DI\ (^{o}F) = 0.4\ (T_{dry} + T_{wet}) + 15 \quad (3.10)$$

Since air temperature (Ta) was measured in degrees Celsius (^{0}C) and the relative humidity (RH) in percentage (%), DI can then be computed by using equation (3.11) below:

$$DI\ (^{o}C) = T\,a - 0.55(1 - 0.01\ RH) * (T\,a - 14.5) \quad (3.11)$$

Decadal averaging was done (using Microsoft Excel) on the discomfort index values obtained to break the discomfort values into three decades (1986 – 1996, 1997 – 2006, and 2007 – 2017). This decadal averaging was done across the five landuse classes of residential, commercial, industrial, institution and administrative; and charts were plotted to present the results.

Thom (1959), found a series of boundary values of the Discomfort index which indicated degrees of discomfort as shown in the Table 1.

Table 1: Thom's Classification of DI ranges

DI Classification	**DI range (ºC)**
No discomfort	DI<21
Under 50% population feels discomfort	21≤DI<24
Over 50% population feels discomfort	24≤DI<27
Most of population suffers discomfort	27≤DI<29
Everyone feels severe stress	29≤DI<32
State of medical emergency	DI≥32

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2.3. Relationship between Land Surface Temperature and Thermal Comfort

LandSat images of three different years (1986, 2002 and 2017) were obtained from the archives of the United States Geological Survey (USGS). The Normalized Difference Vegetation Index (NDVI) is a measurement of the amount and vigor of vegetation at the surface. The reason NDVI is related to vegetation is that healthy vegetation reflects very well in the near infrared part of the spectrum. The value is then normalized to -1<=NDVI<=1 to partially account for differences in illumination and surface slope. The index is defined by equation below:

$$\boldsymbol{NDVI = \frac{NIR-}{NIR+}} \quad \text{(3.2)}$$

Where: NIR and RED are the reflectance in the near-infrared (band4) and red (band3) portion of Electromagnetic spectrum respectively.

The Landsat-5 TM thermal band 6 (10.40-12.50 μm), ETM+ band 6H (10.4 – 12.5 μm) and TIRS10 (10.60 -11.19 μm) has a spatial resolution of 120m, 60m and 100m respectively which are considered suitable as shown by many literatures for capturing the multifaceted intra-urban temperature differences thus makes it effective for urban climate analysis. For the Landsat ETM+ sensor, images in the thermal band are taken twice: one in the low-gain mode (band 6L) and the other in the high-gain mode (band 6H). Band 6L is used to image surfaces with high brightness, whereas band 6H is for low brightness.

Band 6H was used in this study. However, the uniformly resampled Landsat thermal bands were used to retrieve LST over the study area for the three different periods (1986, 2002, and 2017) based on the following steps:

Step 1: The DNs of band 6H from the Landsat TM, ETM+ image were first converted to spectral radiance using:

$$\boldsymbol{L\lambda = \left(\frac{L_{MAX}-L_{MIN}}{QCAL_{MAX}-QCAL_{MIN}}\right) X(DN-1) + L_{MIN}} \quad \text{(3.3)}$$

Where: L is the spectral radiance at the sensor's aperture in $Wm^{-2}\ sr^{-1}\ \mu m^{-1}$; L_{MAX} is the spectral radiance that is scaled to $QCAL_{MAX}$ in $Wm^{-2}\ sr^{-1}\ \mu m^{-1}$; L_{MIN} is the spectral radiance that is scaled to $QCAL_{MIN}$ in $Wm^{-2}\ sr^{-1}\ \mu m^{-1}$; $QCAL_{MAX}$ is the maximum quantized calibrated pixel value (corresponding to L_{MAX}) in DN = 255, $QCAL_{MIN}$ is the minimum quantized calibrated pixel value (corresponding to L_{MIN}) in DN = 1, L_{MAX} and L_{MIN} are obtained from the Meta data file available with the image.

For Landsat 8 with header file data on Radiance Multiplier (M) and Radiance Add (B), the thermal infrared (TIR) band was converted into spectral radiance (L λ) using the approach provided by Chander and Markhan (2003) and the Landsat 7 science Data Users Handbook (2006):

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$L\lambda = (M \times DN) + B$ …………………………………………………………………. (3.4)

Where; M and B refer to the radiance multiplier and add values given in the header file.

Step 2: The effective at-sensor brightness temperature (TB) also known as black body temperature is obtained from the spectral radiance using Plank's inverse function.

$$\boldsymbol{TB = \frac{K2}{ln(K1/L+1)}} \quad \text{(3.5)}$$

TB is effective at-satellite temperature in degree Kelvin; Where T k is radiant surface temperature (in Kelvin); K2 is calibration constant 2 in $Wm^{-2}\ sr^{-1}\ \mu m^{-1}$; K1 is calibration constant 1 in $Wm^{-2}\ sr^{-1}\ \mu m^{-1}$; and L is the spectral radiance at sensor in $Wm^{-2}\ sr^{-1}\ \mu m^{-1}$.

Step 3: Land surface Emissivity Estimation

The temperature values obtained using Equation (3.5) are referenced to a blackbody. Therefore, corrections for spectral emissivity (ε) became necessary according to the nature of land cover. Each of the LULC categories was assigned an emissivity value by reference to the emissivity classification scheme by Snyder *et al*. (1998). A heterogeneous surface (that is, a mixture of the bare-soil, exposed water surface and vegetation) was considered in this study. The emissivity of an heterogeneous surface (a mixed pixels) was computed using Equation (3.6) below, taking into account proportion of vegetation in each pixel (fv) which was also estimated using Equation (3.7) (Sobrino*et al*., 2004) and cavity effect which is due to surface roughness (C_λ) calculated by equation (3.8) using geometrical (shape) factor 'F' with the mean value of 0.55 (Sobrino *et al.*, 1990).

$$\varepsilon = \varepsilon v\lambda \times f v + \varepsilon s\lambda \times (1 - fv) + C\lambda \quad \text{(3.6)}$$

$$\boldsymbol{fv = \left[\frac{NDVI - NDVIs}{NDVIv - NDVIs}\right] 2} \quad \text{(3.7)}$$

$$C_\lambda = (1 - \varepsilon s_\lambda) \times \varepsilon v_\lambda \times F' \times (1 - fv) \quad \text{(3.8)}$$

Where; NDVI is the Normalized Differential Index as computed with Equation 3.2 for each respective years considered in this study. NDVIs and NDVIv are Normalized Difference Vegetation Index Threshold values for soil pixels (NDVIs = 0.2) and pixels of full vegetation (NDVIv = 0.5) respectively as proposed by Sobrino *et al*., (1990) and Sobrino *et al*., (2008). εs and εv are the emissivity (ε) of soil pixels and full vegetation pixels with the mean value of 0.97 and 0.99 respectively (Sobrino *et al*., 2004).

Step 4: The calculated radiant surface temperatures were successively corrected for emissivity using the equation developed by

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$$LST = \frac{TB}{1+\left(\frac{\lambda * TB}{\rho}\right) * \ln\varepsilon} \quad (3.9)$$

Where LST is Land Surface Temperature (in Kelvin), TB is radiant surface temperature (in Kelvin), λ is the wavelength of emitted radiance (11.5 μm), ρ is h×c/σ (1.438×10^{-2}mK), h is Planck's constant (6.26×10^{-34}Js), c is the velocity of light (2.998×10^{8} m/sec), σ is Stefan Boltzmann's constant (1.38×10^{-23}JK^{-1}) and ε is emissivity.

Step 5: Finally, the LSTs were converted into Celsius (Tc) using

Tc = LST – 273

3. Results and Discussion

3.1. Variation of Human Discomfort Index across Different Landuse Types

The high resolution IKONOS image was classified into five landuse classes (see Figure 2) which are: institutional (tertiary), residential, commercial, industrial and administrative; and each landuse occupy landmasses as shown in Table 2 and Figure 3 below respectively. The result shows that residential accounted for the highest landuse with 78%, followed by administrative, institutional, industrial and commercial with 13%, 4%, 3% and 2% respectively.

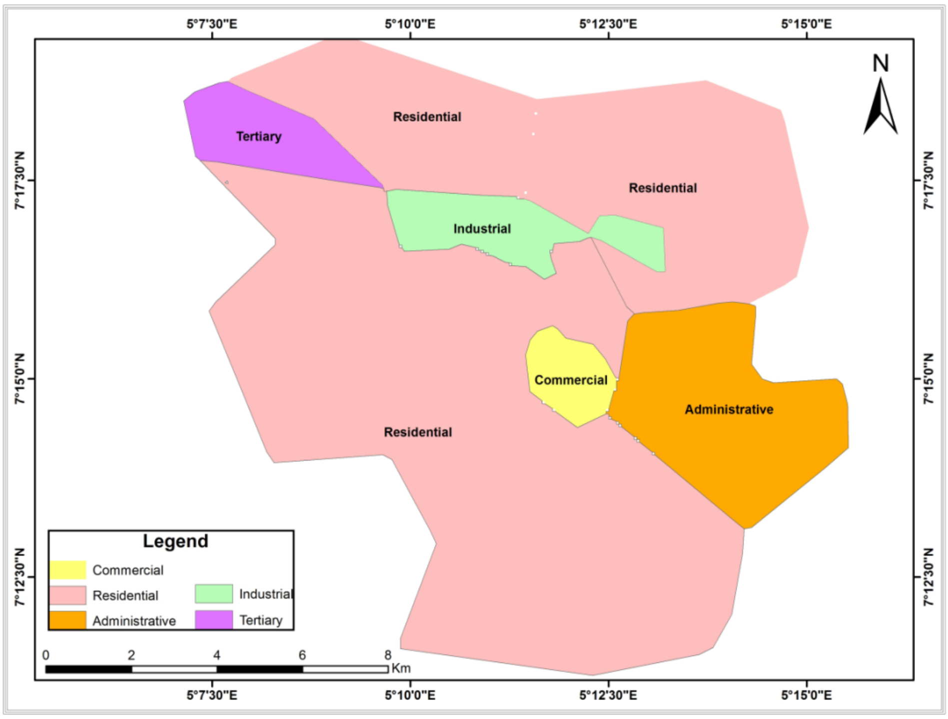

Figure 2: Landuse classes in Akure Metropolis

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Table 2: Area covered by each Landuse class (Sq.Km)

CLASS	AREA (Sq.Km)	AREA (%)
ADMINISTRATIVE	18	11.6
COMMERCIAL	3	2.0
INDUSTRIAL	7	4.5
RESIDENTIAL	121	78
INSTITUTIONAL	6	3.9
TOTAL	**155**	**100**

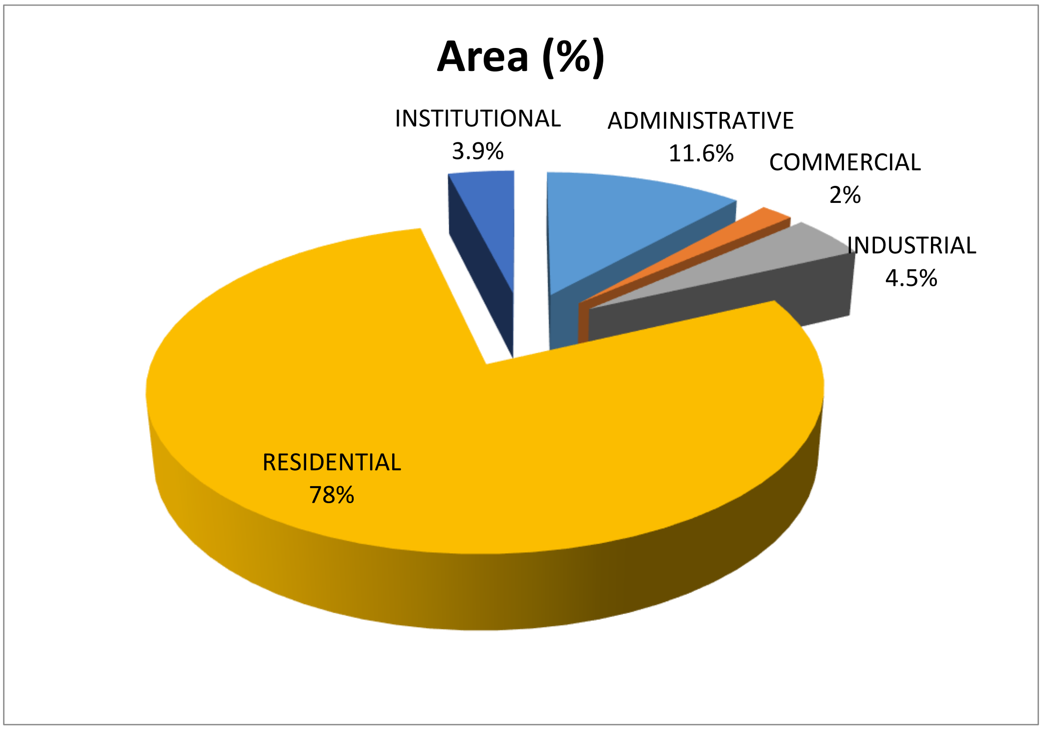

Figure 3: Percentage of landmass occupied by each landuse in the study area

3.1.1. Annual and Decadal Discomfort Index from 1986-2017

The discomfort index as calculated using the Thom's model was derived across the five landuse classes (administrative, commercial, industrial, institutional and residential) and averaged on an annual (1986-2017) basis as well as on a decadal (10 years) basis (1986-1996, 1997-2006 and 2007-2017). Figure 4 below shows the annual averages (1986-2017) of the Discomfort index in Akure. The 1986-1996, 1997-2006 and 2007-2017 discomfort index decadal averages are as shown in figures 5, 6 and 7 below.

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Thom (1959) proposed a discomfort index classification range as shown in Table 1 above. From Table 1 and Figure 4, it can be inferred that over a period of 31years, over 50% of the population in Akure are experiencing thermal discomfort. A critical analysis of the Decadal Discomfort Index across the five (5) landuse classes shows that the residential landuse class experiences the highest amount of discomfort relative to the other landuse classes.

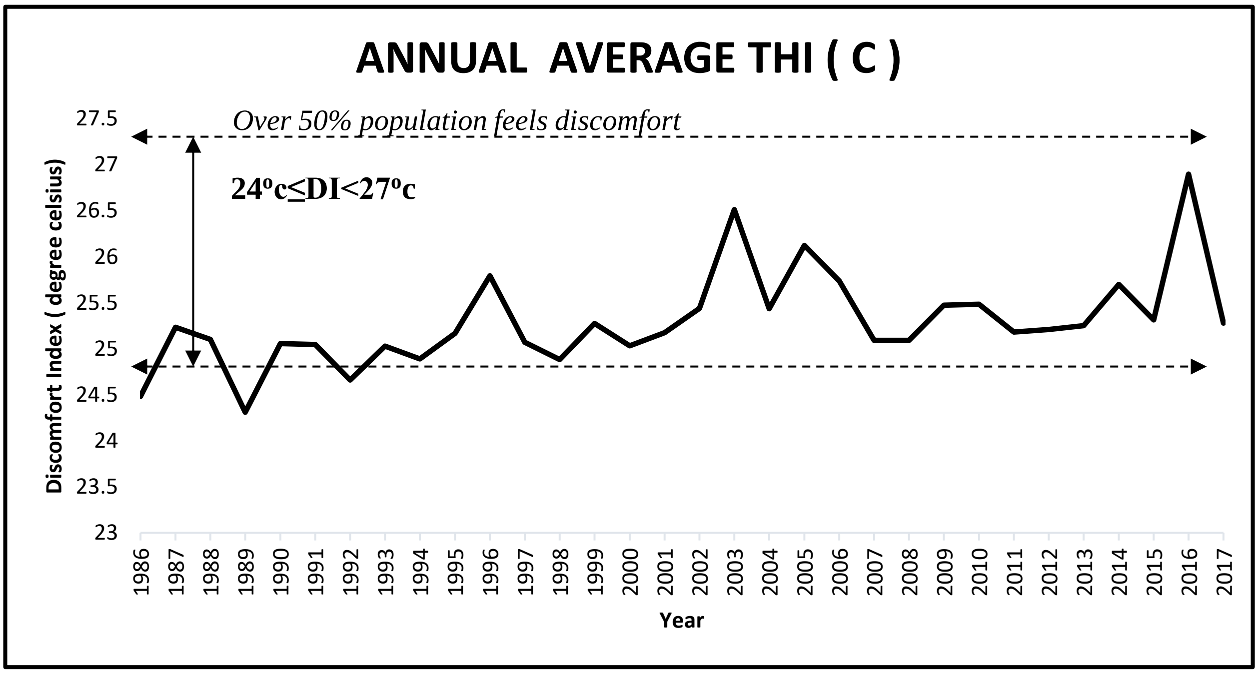

Figure 4: Annual Discomfort Index (1987-2017)

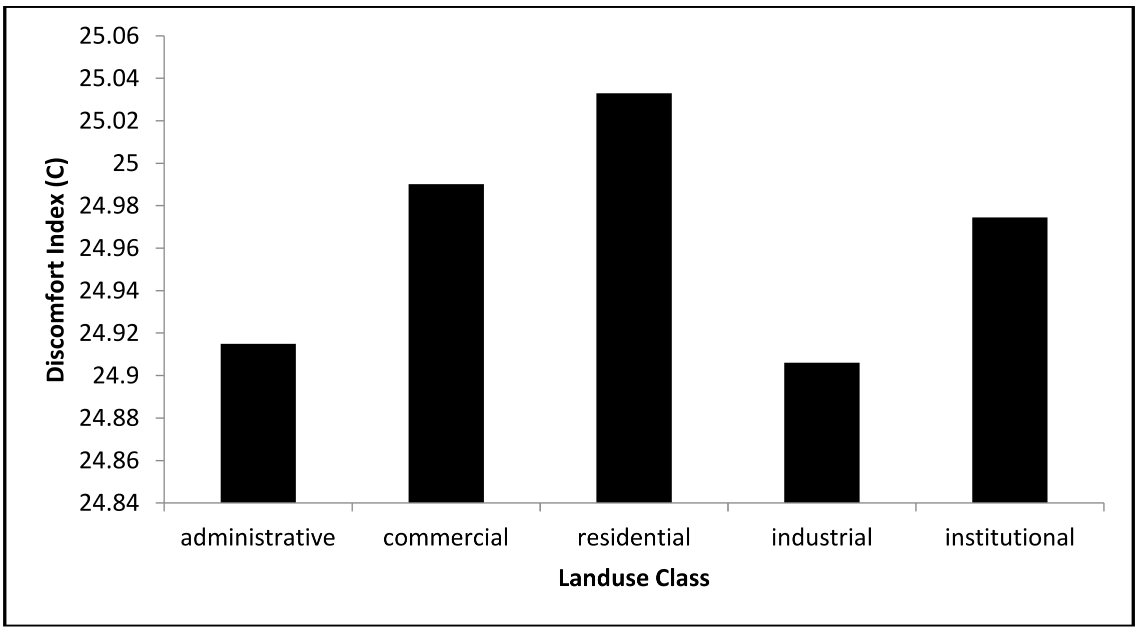

Figure 5: Decadal Discomfort Index across Landuse classes (1986-1996)

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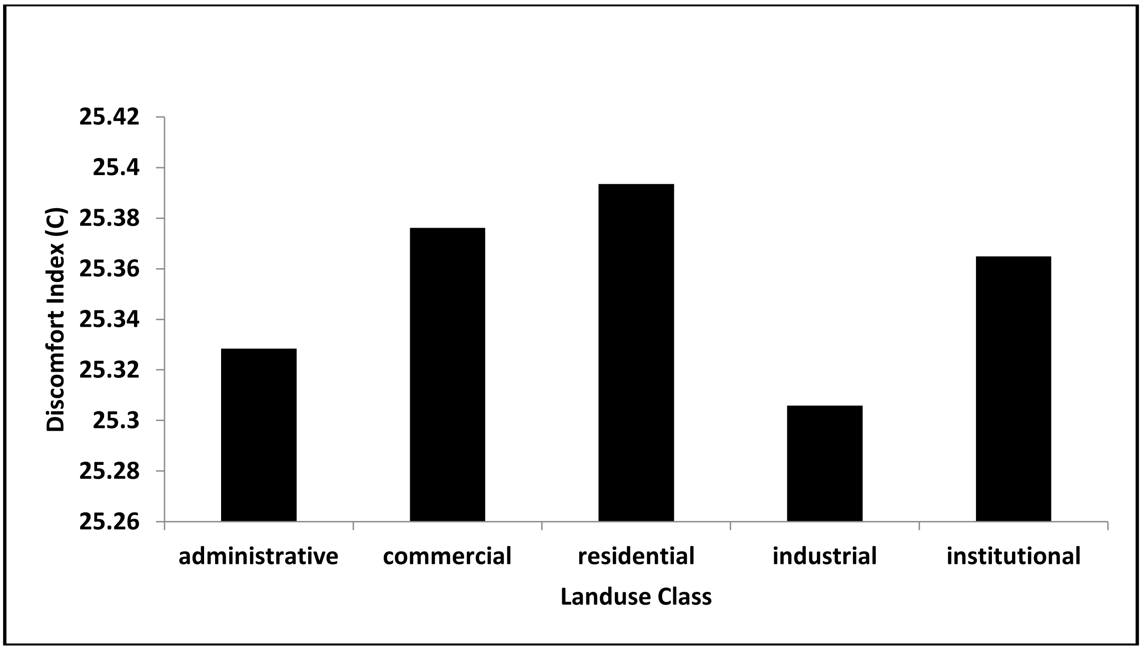

Figure 6: Decadal Discomfort Index across Landuse classes (1997-2006)

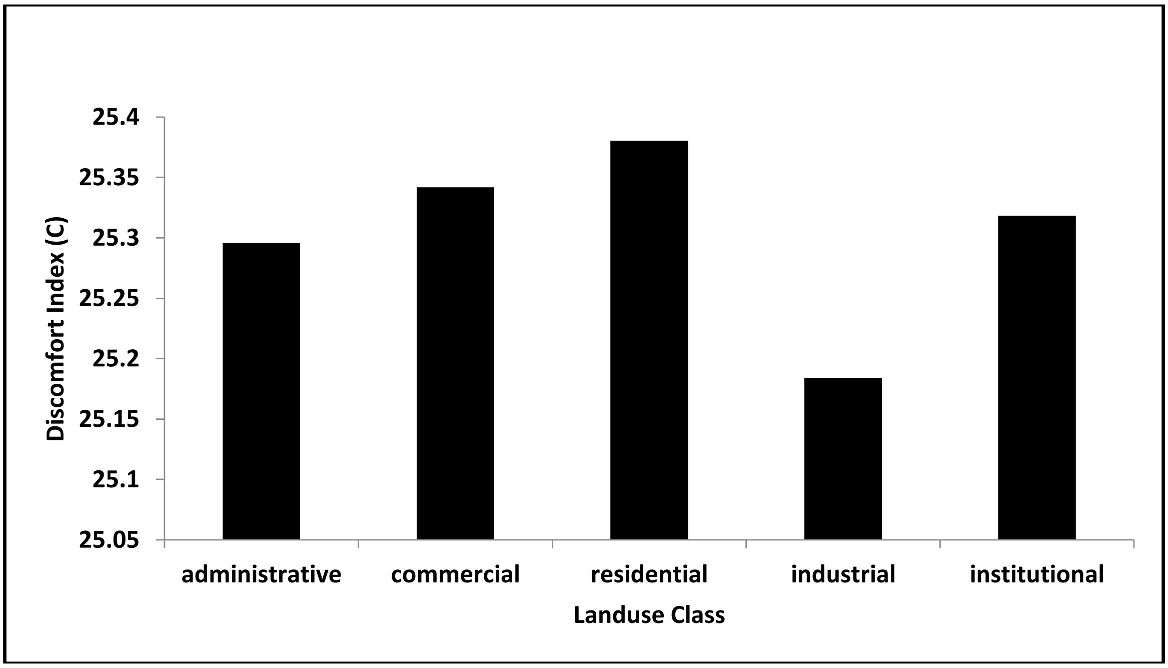

Figure 7: Decadal Discomfort Index across Landuse classes (2007-2017)

3.2. Relationship between Land Surface Temperature and Thermal Comfort

The temperature profile shown in the Figures 8, 9 and 10 below clearly demonstrates the land surface temperature profile over the study area for the years 1986, 2002 and 2017.It was observed in 1986 from Figure 8 below, that the surface temperature within the study area ranged from 20^0C to 30^0C, with 30^0C being the highest value. The temperature range on the high scale of 24^0C - 30^0C can be seen

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to spread within the core areas of Residential, Administrative and Commercial. While the tertiary and the industrial classes were within the lower scales of 20^0C – 24^0C for the year 1986.

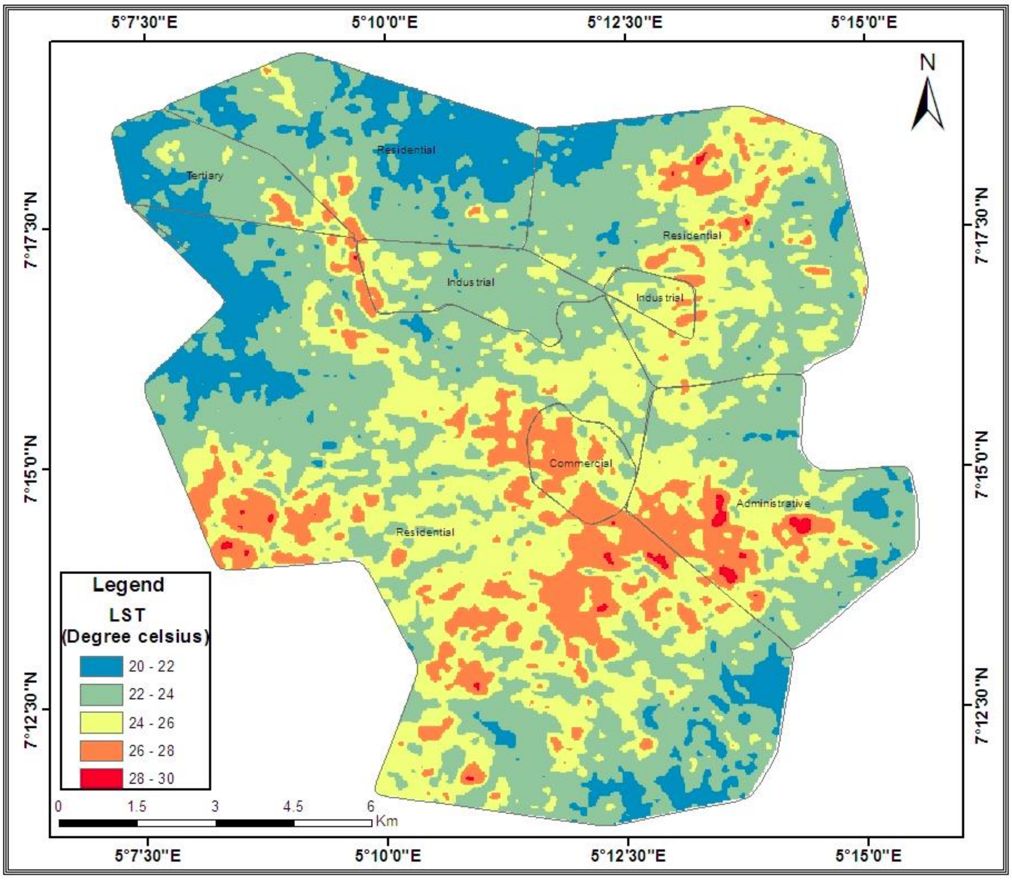

Figure 8: Land Surface Temperature of Akure (1986)

In 2002, the surface temperature range in Akure increased, having the range from 22ºC – 32ºC. The high values between 26ºC and 32ºC were seen from Figure 9 below to have spread to the core areas of residential, administrative, industrial, tertiary and commercial.

For the year 2017, there was an increase in the land surface temperature across Akure as shown in Figure 10 below; the lowest LST value was 24ºC, while the highest LST value was 34ºC. It was observed that for the year 2017, the high values between 28^0C and 34^0C were seen to have spread across all the landuse classes.

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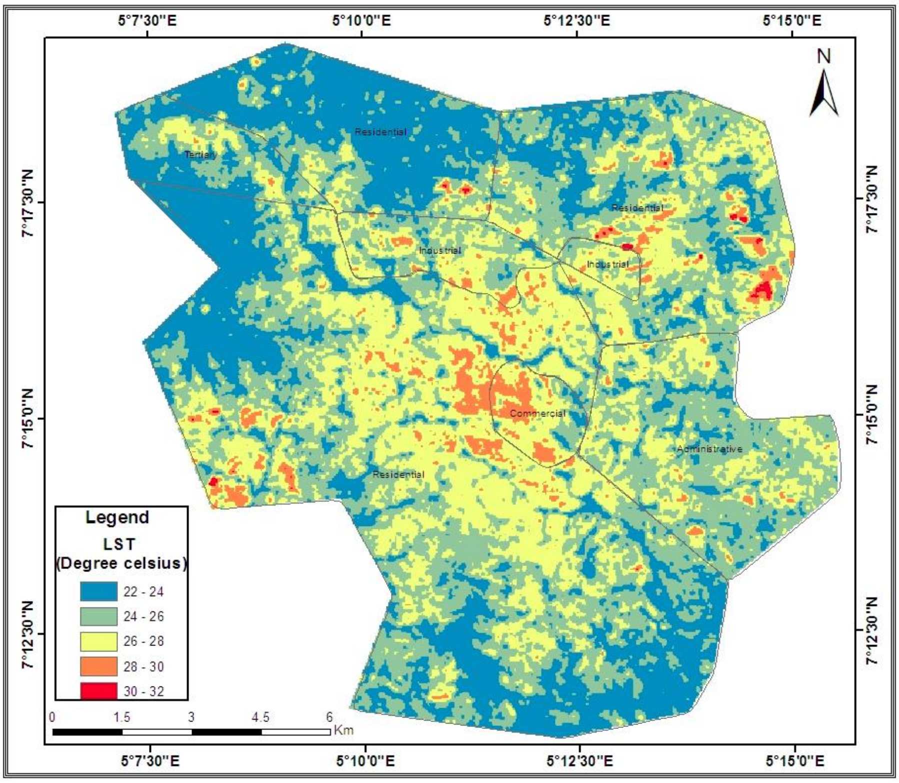

Figure 9: Land Surface Temperature of Akure (2002)

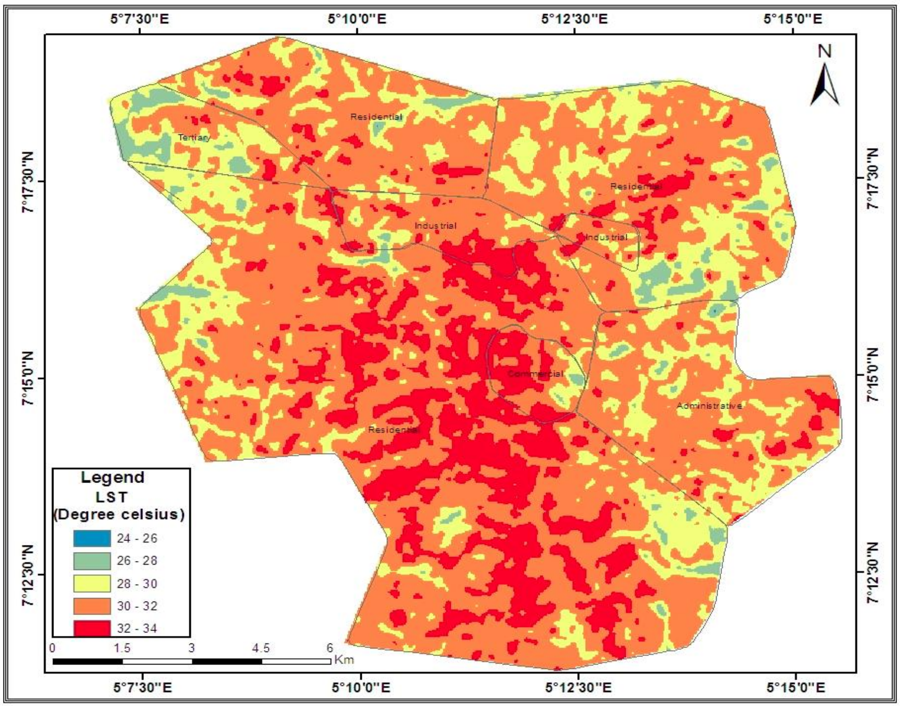

Figure 10: Land Surface Temperature of Akure (2017)

Figures 11, 12, and 13 below shows that there is a strong positive correlation (directly related) between LST and DI. Which means the increase in the land surface temperature in Akure will bring about a corresponding increase in the discomfort index. The correlations coefficient for each year is

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summarized in table 3 below. The correlation coefficients (R) were found to be; 0.9886, 0.9966 and 0.9364 in 1986, 2002 and 2017 respectively. The strong correlation observed between surface temperatures and discomfort index suggests the potential of using linear regression to predict discomfort index if LST values are known.

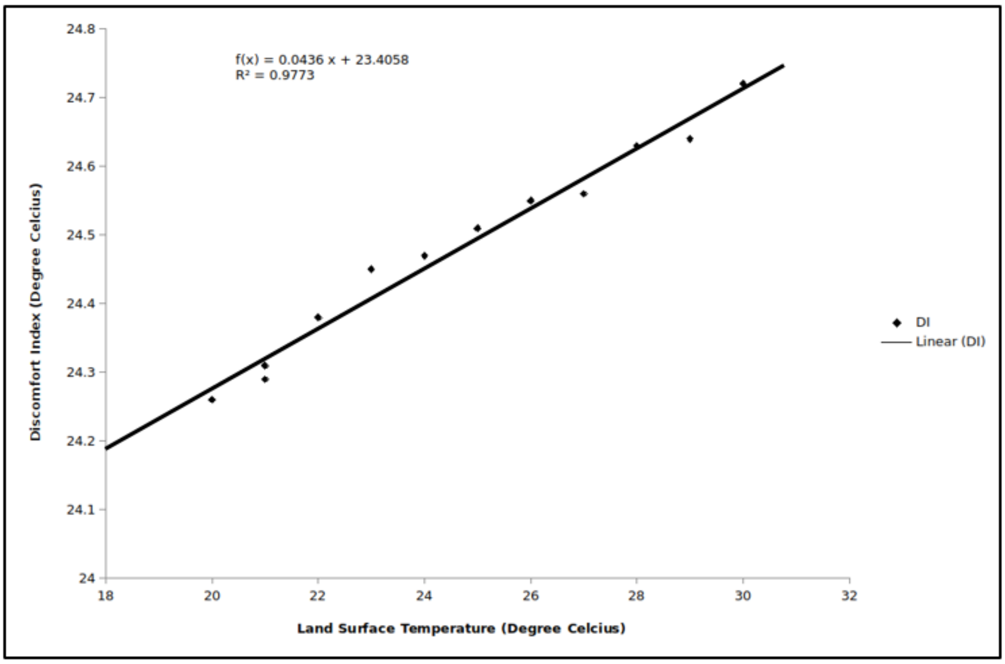

Figure 11: Linear Regression between LST and DI (1986)

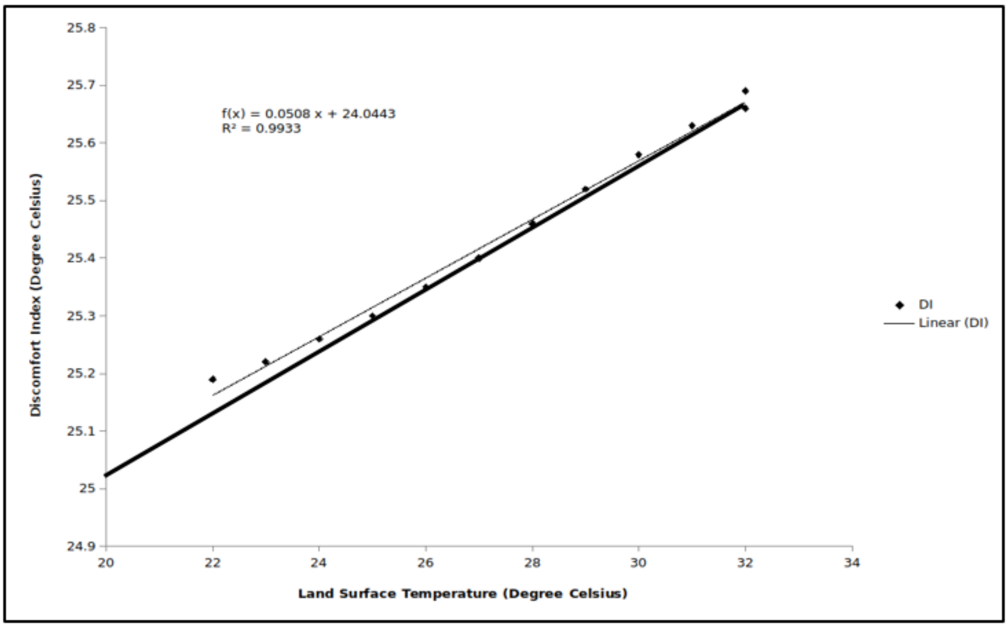

Figure 12: Linear Regression between LST and DI (2002)

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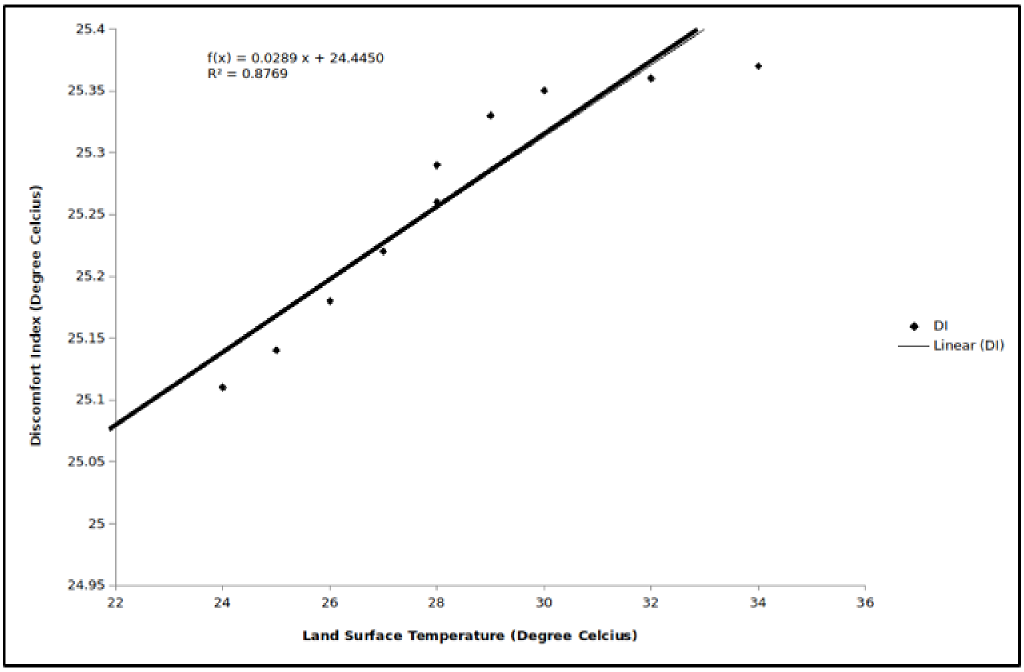

Figure 13: Linear Regression between LST and DI (2017)

Table 3: Correlation coefficient values for each year

RELATIONSHIP BETWEEN LAND SURFACE TEMPERATURE AND DISCOMFORT INDEX		
YEAR	Coefficient of determinant (R^2)	Coefficient of correlation (R)
1986	0.977335951	0.98860303
2002	0.993265881	0.996627253
2017	0.876901822	0.936430362

Generally, it is seen that the value of LST increased from 1986 to 2017 due to the rapid urban growth in the study area (Akure).

4. Conclusions

This study has examined the spatio-temporal pattern of thermal comfort using the Thom's Discomfort Model. In this study, the pattern of the human thermal comfort was analyzed while taking into consideration the influences of anthropogenic factors like land surface temperature, in other to ascertain the effects of human activities on the thermal comfort of Akure. Temperature and relative humidity data gotten from era interim were used to estimate for the discomfort index. The DI values observed varied from 24^{0}C -25.4^{0}C, over the 31years that was examined, indicating that human comfort cannot be guaranteed to be in the thermal sensation of no stress in the study area according to the classification made by Thom (1959).

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It can be concluded that there is a relationship between land surface temperature and the thermal comfort of Akure. The study reveals that the environment of Akure is not comfortable for most dwellers. Being a 31year study, this study is a representation of the climatic trend over Akure and thus readily very likely to be of help in decision making on various levels, including health, tourism and regional planning.

Potential Conflicts of Interest

The author hereby declares that there was no conflict of interest in the process of carrying out this study.

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