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Monitoring Monthly and Seasonal Dynamics of Subsurface Urban Heat Island and Possible Mitigation Measures in Enugu Metropolis, Nigeria

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Abstract
This study analysed the monthly and seasonal dynamics of subsurface urban heat island in Enugu metropolis, using secondary soil temperature data set that was sourced from the Nigerian Meteorological Agency. The descriptive statistical tool used was the line graph. The study showed that the monthly subsurface urban heat island intensity peaks at 0.6 ^{0}C in May and remains fairly constant from September to February. It also revealed that the seasonal subsurface urban heat island intensity peaks at 0.5 ^{0}C in spring (March, April and May) before staying relatively stable from summer (June, July and August) to winter (December, January and February). From the study, it was clear that the urban heat island effect occurred in the subsurface in Enugu, as it does above the ground. Therefore, this study recommends the creation of gardens and parklands and direct tree planting as part of the mitigation measures to this problem.
Keywords: Enugu, mitigation, soil temperature, subsurface, urban heat island, urbanisation
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1. Introduction

In the process of urbanisation, the temperature is the most affected climatic factor (Turkoglu, 2010), with its resultant impacts on the environment generally termed as urban heat island (Huang, Taniguchi, Yamano & Wang, 2009). Urban heat island (UHI) refers to the local climatic warming in urban areas such that it becomes warmer than its non-urbanised surroundings. It has four types: the subsurface UHI (SubUHI), surface UHI, boundary-layer UHI and canopy-layer UHI; with the last two collectively referred to as "air" or "atmospheric" UHI to give three broad categories (Luo & Asproudi, 2015; Huang *et al.*, 2020). The SubUHI or "underground" UHI specifies the relative warmth of urban ground temperatures against the rural background (Zhan *et al.*, 2014).

Analysing the SubUHI has been done in different cities across the world. For example, measurements by the Minnesota Pollution Control Agency (2001) and simulations by Taniguchi and Uemura (2005) provide evidence of conduction-based warming of the subsurface due to urbanisation. Ferguson and Woodbury (2004; 2007) reported that temperatures measured in boreholes inside the city of Winnipeg were several degrees higher than those recorded at the same time in agricultural areas in the immediate neighbourhood of the city. Likewise, Nitoui and Beltrami (2005) found increases in soil temperature of several degrees after deforestation. On the other hand, Šafanda, Rajver, Correia and Dědeček (2007) observed unusual warming in the subsurface temperature at a monitoring station in Prague and proposed that it was due to the recent construction of structures on the ground surface around the station. Yamano *et al.* (2009), who logged over 100 boreholes in several Asian megacities, revealed substantial temperature increases during the past decades, much more than could be inferred by analytical inversion from logs in rural vicinity.

Since the establishment of the Enugu Capital Territory Development Authority in 2009 (Munachiso, 2020), there have been many studies on the UHI in Enugu (for a detailed review, refer to Enete, 2015). For instance, the spatial extent of UHI and the applicability of Landsat Enhanced Thematic Mapper in UHI research was the main focus in few studies (Adinna, Enete & Okolie, 2009; Enete & Okwu-Delunzu, 2013) while the place of UHI in urban planning was pointed out elsewhere (Adinna, Enete, Ogbonna & Okolie, 2009). A follow-up study by Enete, Officha and Ogbonna (2012) focused on thermal analysis and discomfort level caused by UHI while rainy season (Enete & Alabi, 2012a) and dry season (Enete & Alabi, 2012b) UHIs in Enugu urban have also been conducted. Similarly, integrating the concept of air pollution tolerance index (Enete, Ogbonna & Officha, 2012) in the choice of trees for UHI reduction (Enete, Alabi & Chukwudelunzu, 2012) further advanced UHI knowledge in Enugu urban. Yet, despite previous studies confirming the presence of UHIs in Enugu urban, limited knowledge still exist on subsurface warming.

At the shallow layer (<10 m; Zhan *et al.*, 2014), the SubUHI intensity (SubUHII) exhibits diurnal, monthly and seasonal variabilities (Turkoglu, 2010; Liu, Shi, Tang & Gao, 2011; Tang *et al.*, 2011; Shi, Tang, Gao, Liu & Wang, 2012; Luo & Asproudi, 2015). However, the emphasis here is on the monthly and seasonal variations since the daily SubUHII is fairly noisy, "with high-amplitude variations in short time scale" (Tang *et al.*, 2011; Shi *et al.*, 2012). In terms of its monthly variations, Tang *et al.* (2011) revealed a significant SubUHII that stretches from

0.62 ^{0}C (October) to 2.0 ^{0}C (July) in Nanjing. A year later, a different study in Nanjing by Shi *et al.* (2012) reported a significant SubUHII that ranges from 1.34 ^{0}C (November) to 3.05 ^{0}C (July).

On the contrary, Luo and Asproudi (2015) found that the monthly SubUHII extends from 0.2 ^{0}C (July) to 3.5 ^{0}C (December) in London, and attributed it to the dissimilar climates and anthropogenic heat patterns in these cities. Unlike the 'U-shaped' SubUHII curve shown in Luo and Asproudi (2015, Fig. 5), this curve has a 'W-shape' for other studies (Tang *et al.*, 2011, Fig. 6; Shi *et al.*, 2012, Fig. 3). Based on the seasonal variations, SubUHII is higher in warmer seasons in Ankara (Turkoglu, 2010). In Nanjing, according to Tang *et al.* (2011), it is between 0.84 ^{0}C (autumn) and 1.51 ^{0}C (summer) while Shi *et al.* (2012) found the order of SubUHII to be summer (2.45 ^{0}C) > winter (2.03 ^{0}C) > spring (1.63 ^{0}C) > autumn (1.53 ^{0}C). Elsewhere in London, Luo and Asproudi (2015) found a contrasting result and they revealed that SubUHII is larger in colder seasons (autumn and winter).

In the present study, knowledge from the mid-latitude studies is being transferred to the Enugu context. As such, the study seeks to determine the monthly and seasonal dynamics of SubUHI in Enugu metropolis. The corresponding research question states thus: What are the monthly and seasonal changes in SubUHI in Enugu?

2. Materials and Methods

2.1 Study Area

The study area is Enugu urban, which is the capital of Enugu State in Southeastern Nigeria. It is composed of Enugu East, Enugu North and Enugu South Local Government Areas (LGAs), and is bounded by various LGAs in the following directions: in the north by Igbo-Etiti and Isi-Uzo, south by Nkanu West, east by Nkanu East and west by Udi. It lies approximately within Latitudes 6^{0}21'N and 6^{0}29'N of the Equator and Longitudes 7^{0}26'E and 7^{0}35'E of the Greenwich meridian (Fig. 1).

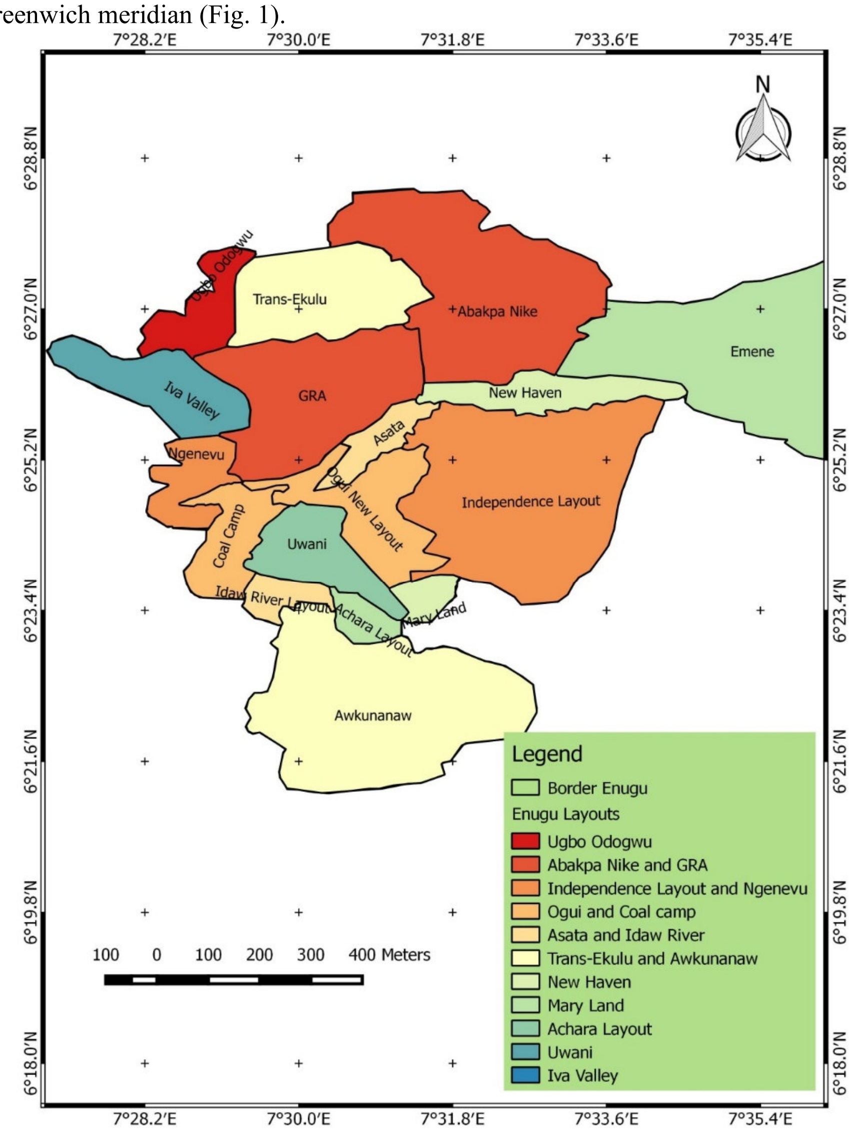

Figure 1. The Wards in Enugu Urban (Source: GIS Lab, Department of Geography & Meteorology, NAU, Awka)

The past census figures confirm the growth of this city. Enugu urban had a population of 464,514 and 717,291 in 1991 and 2006 respectively as well as an estimated population of 833,373 in 2011 (National Population Commission, as cited in National Bureau of Statistics, 2012). The city is an ideal location for this study; besides being the ninth most populous city in Nigeria (Okeke, Sam-Amobi & Okeke, 2020), it is the largest city in Enugu State (Enete & Alabi, 2012a).

Enugu urban is located in the Tropical Rainforest zone that relates to the Tropical Wet and Dry (Aw) climate of the Köppen-Geiger-Pohl classification system (Peel, Finlayson & McMahon, 2007). The general relief comprises a gently undulating plain with low hills and steep valleys, creating a dual division of escarpment and lowland zones. It lies below 300 m northwest on the Cross River basin and is characterised by a dendritic drainage pattern that is dominated by two major river systems: the larger, Ekulu river system (northwards) and the Nyaba river system (southwards).

Human activities have reduced Enugu's vegetation from tropical rainforest to derived guinea savanna vegetation (Ogbonna, Ugbogu, Otuu, Ohakwe & Inya-Agha, 2014; Okeke *et al.*, 2020), otherwise described as a "rainforest-savanna ecotone" (Anyadike, 2002), with a hydrologic ratio of less than 0.75 (Adefolalu, 1986). A well-developed transportation network plays an important role in stimulating production in the city. Enugu is an hour's drive from Onitsha, one of the biggest commercial cities in Africa, and takes two hours from Aba, another very large commercial city, both of which are trading centres in Nigeria (Enete & Alabi, 2012a; 2012b).

2.2 Data Need

Soil temperature data sets over 21 years (at depths of 5, 10, 20, 30, 50 and 100 cm, respectively) were collected for urban and rural areas and examined. Even though the groundwater temperature exists as an alternative, the soil temperature was chosen as the subsurface temperature because it is more accessible and affordable (Benz, Bayer, Goettsche, Olesen & Blum, 2016; Benz, Bayer & Blum, 2017). These depths were chosen because they are the depths at which soil temperatures are measured at the Nigerian Meteorological Agency (NIMET), Enugu (see Fig. 2) and fall within the "shallow layer" definition given by Zhan *et al.* (2014). For this study, the rural area was used loosely to refer to the surrounding area. Unlike surface air temperature (SAT), the soil temperature is not commonly available (Qian, Gregorich, Gameda, Hopkins & Wang, 2011). This informed the choice of the study's duration, which is considered suitable for this analysis. Records from January 2000 to December 2020 was selected for this study.

Furthermore, the calculation of the differences or SubUHIIs at different time scales was done (SubUHII: urban soil temperature − rural soil temperature). For each depth in the urban and rural data set respectively, the 21-year average was obtained as a single value for each month. Likewise, the resulted (21-year averaged) monthly soil temperatures across the six depths were also averaged to obtain a single value to represent all the depths per month. This output was used to obtain the monthly dynamics. For the seasonal dynamics, the same idea was applied further to get the averaged seasonal differences from the output used to achieve that of the monthly dynamics. In the reviewed literature, the seasons were grouped into four: spring (March, April and May, MAM), summer (June, July and August, JJA), autumn (September, October and November, SON) and winter (December, January and February, DJF). For comparability of the results, this categorisation was applied in this study even when only two seasons, rainy and dry, exist.

2.3 Data Sources and Method of Collection

All the data sets used in this study were sourced from the NIMET headquarters in Abuja as secondary data. At the observatory unit of NIMET, Enugu, regular meteorological observations are provided, including soil temperatures that are collected every six hours (0000, 0600, 1200 and 1800 GMT) by the meteorological observers. A mercury-in-glass soil thermometer (Casella-London immersion) that is spaced at about 65 cm apart (Fig. 2) was used to measure the soil temperature at 5, 10, 20, 30, 50 and 100 cm depth points, and recorded on "Form Met 113". The daily mean soil temperatures are calculated for each soil depth and averaged to get the monthly mean required for this study. The rural soil temperatures were downscaled by NIMET; this was done 40 km away from the observatory unit using an application known as "grid" (Jimoh, personal communication, January 12, 2022). Further attempts to get more information about the workings of this application and the stepwise guide to using it were unfortunately declined.

Figure 2. Soil thermometers at NIMET, Enugu

The thermometers are spaced roughly 65 cm apart and arranged orderly to allow for easy reading of the soil temperature at six depths (from left to right): 5, 10, 20, 30, 50 and 100 cm. As the soil temperature increases, the mercury in the bulb extends and rises. When the soil temperature drops, the mercury shrinks and falls down the tube

2.4 Method of Data Analysis

There are other ways to describe quantitative data (including histogram, bar chart, pie chart and scatterplot) but a line graph (also called line plot or line chart) was employed to answer the research question that states thus: "What are the monthly and seasonal changes in SubUHI in Enugu?" (see Section 1). This graph is very similar to a scatterplot but the difference is that a line was created to connect each data point and an ordinary least square line was not drawn. Unlike scatterplot, a line graph is better when the focus is to describe short-term fluctuations (for example monthly and seasonal dynamics), so no smoothing function was applied.

In smoothing, variations that last over a short period are implicitly assumed as unimportant (Burt, Barber & Rigby, 2009) and applying it would have defeated this objective. Also, because "periodic" indicates that "identical or almost identical patterns" already exist (Anyadike, 2009), unlike in scatterplot that is used to verify whether or not a relationship exists, this graph becomes more useful to show the nature of this relationship. Hence, it was utilised to instantly visualise the 'journey' of SubUHI which was useful to create a narrative. This has been applied successfully in literature to describe the short-term dynamics of SubUHI (Tang *et al.*, 2011; Shi *et al.*, 2012) and can be done on SPSS or with the aid of Microsoft Excel.

3. Results and Discussion

The average monthly temperatures for urban and rural soil along the six depths were shown in Fig. 3(a). The minimum monthly temperature was observed in August, at 27.4 ^{0}C in the urban area and 26.9 ^{0}C in the rural area. The maximum monthly temperature was observed in March, at 33.2 ^{0}C in the urban area and 32.7 ^{0}C in the rural area. These are generally in line with the corresponding SAT results shown in Appendix A and revealed that soil temperature is significantly related to SAT. The monthly difference or monthly SubUHII calculated from Fig. 3(a) was shown in Fig. 3(b). The monthly SubUHII peaks at 0.6 ^{0}C in May and remains fairly constant from September to February.

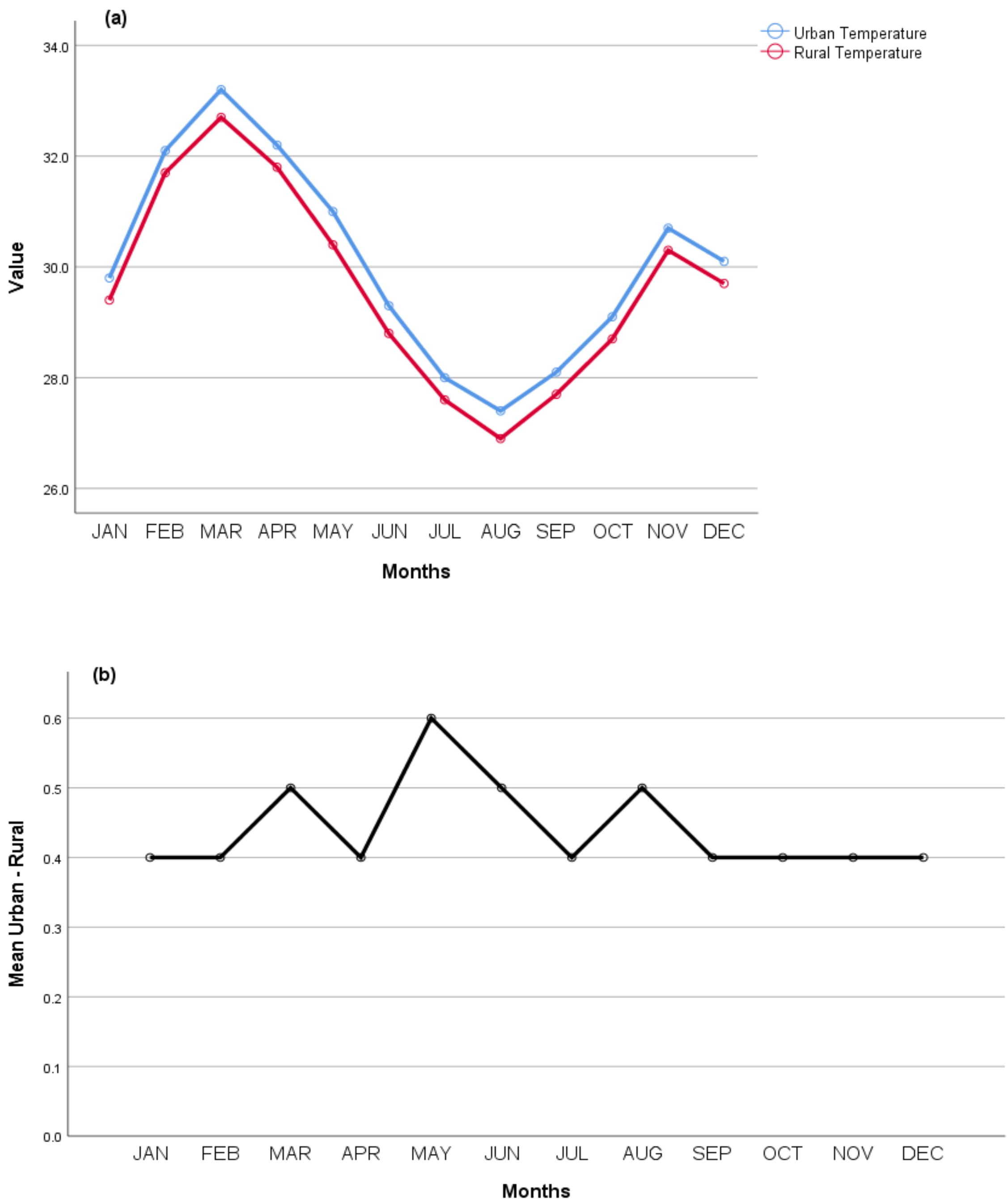

Figure 3. The Average Monthly Temperatures of Urban and Rural Soil (a) and the Corresponding SubUHII (b)

Presentation of the average seasonal temperatures for urban and rural soil can be found in Fig. 4(a); they were calculated from Fig. 3(a). Understandably, the minimum and maximum seasonal temperatures were seen in summer (JJA) and spring (MAM). Again, these are typically consistent with the corresponding SAT results (see Appendix B), re-emphasising the relationship between soil temperature and SAT. The seasonal difference or seasonal SubUHII calculated from Fig. 4(a) was shown in Fig. 4(b). Each season has a SubUHII of at least 0.4 ^{0}C, peaking at 0.5 ^{0}C in spring and staying relatively stable at 0.4 ^{0}C from summer to winter (DJF).

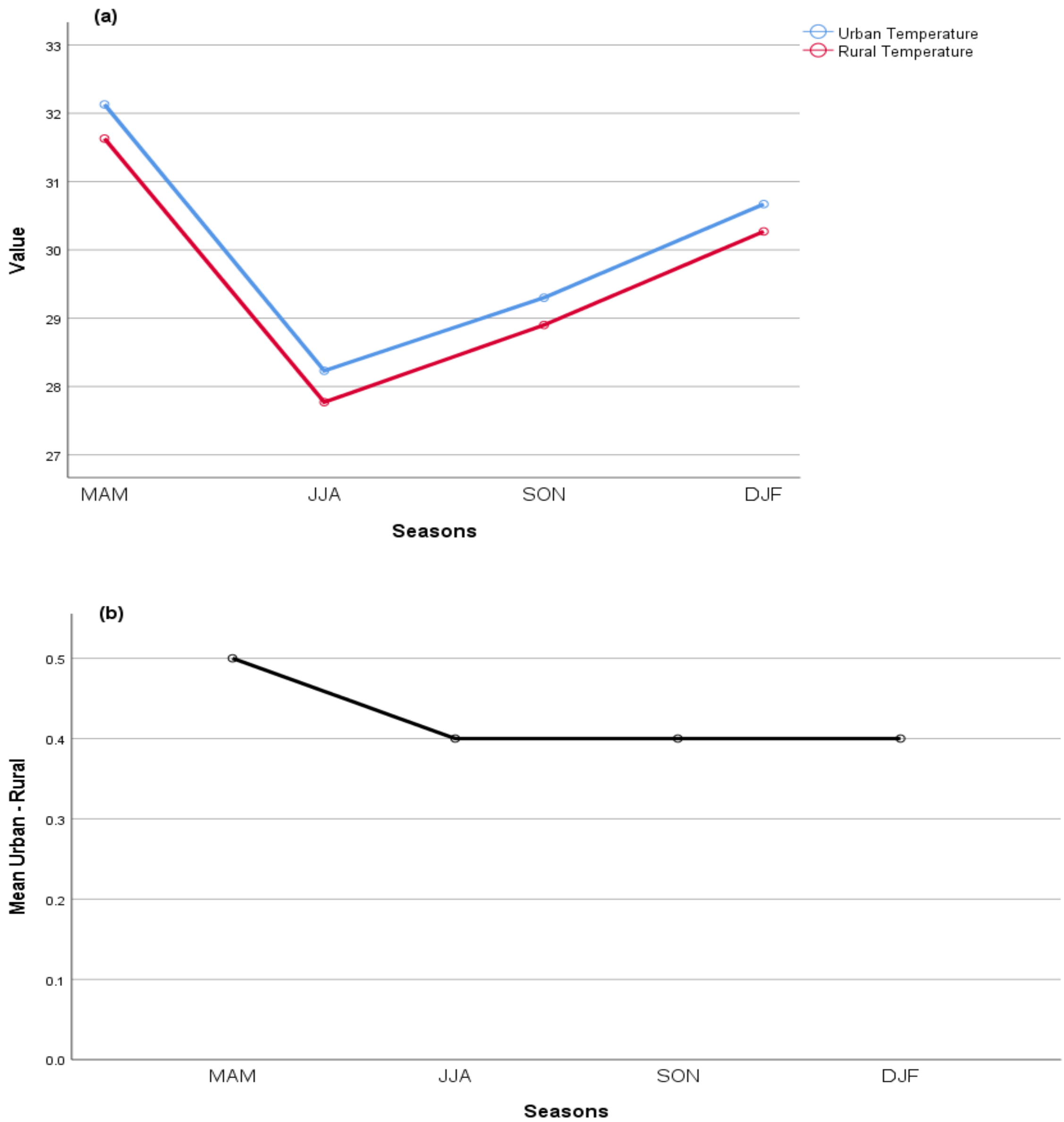

Figure 4. The Average Seasonal Temperatures of Urban and Rural Soil (a) and the Corresponding SubUHII (b)

The maximum soil temperature (Fig. 3[a]) occurred in March because this is when the global solar radiation peaks and agrees with the findings of Chiemeka (2010) in Uturu, Abia State. The minimum soil temperature was observed in August and is different from Chiemeka (2010), who reported January to have the lowest temperature as his study was from December to April and did not include August. The fact that the urban soil temperature in Fig. 3(a) is above that of the rural suggests the presence of SubUHI, with its monthly intensity peaking in May — which is different from other studies conducted in Nanjing (Tang *et al.*, 2011; Shi *et al.*, 2012) and London (Luo & Asproudi, 2015). Generally, the seasonal SubUHII is maximum at the season having the month where the highest soil temperature occurred: spring for this study (see Fig. 3 and Fig. 4) and summer (Tang *et al.*, 2011; Shi *et al.*, 2012) and autumn (SON; Luo & Asproudi, 2015) for previous studies. This respective monthly and seasonal difference in result could be due to the dissimilar climates and anthropogenic heat patterns in these cities.

4. Conclusion

This study showed that the monthly SubUHII peaks at 0.6 ^{0}C in May and remains fairly constant from September to February. It also revealed that the seasonal SubUHII peaks at 0.5 ^{0}C in spring before staying relatively stable from summer to winter. From the study, it was clear that the UHI effect occurred in the subsurface in Enugu, as it does above the ground.

Based on the findings, this study provides some measures for the mitigation of Enugu SubUHI:

- Creation of gardens and parklands: Because vegetation ensures that the soil surrounding a building is cooler and protects, reflects and diffuses incoming solar radiation, it should be introduced extensively and carefully.
- Direct tree planting: Trees provide enormous benefits and can serve as a useful mitigation tool; hence, new trees should be planted while maintaining the old ones. On the choice of trees to be planted, Enete, Alabi *et al.* (2012) and Enete, Ogbonna *et al.* (2012) recommended Mango (*Mangifera indica*) among others.
- Reduction of urban vehicles: The role of anthropogenic heat in increasing the UHI effect is well documented, hence a proper urban public transportation system is vital to reduce the heat originating from motorised vehicles.
- Use of permeable pavement in parking lands: Instead of using the more common asphalt and low-albedo materials, alternative construction materials (polyvinyl chloride, concrete, among others) can be used. This will ensure that parking lands can be shaded and covered through the planting of vegetation around its perimeter and whole surfaces, helping to improve the reflectivity.
- Reduction of landfills: Since increment in SubUHI occurs due to further non-climatic disturbances, including landfills, designing and implementation of integrated waste management can help to control the amount of heat these wastes would have generated over time.

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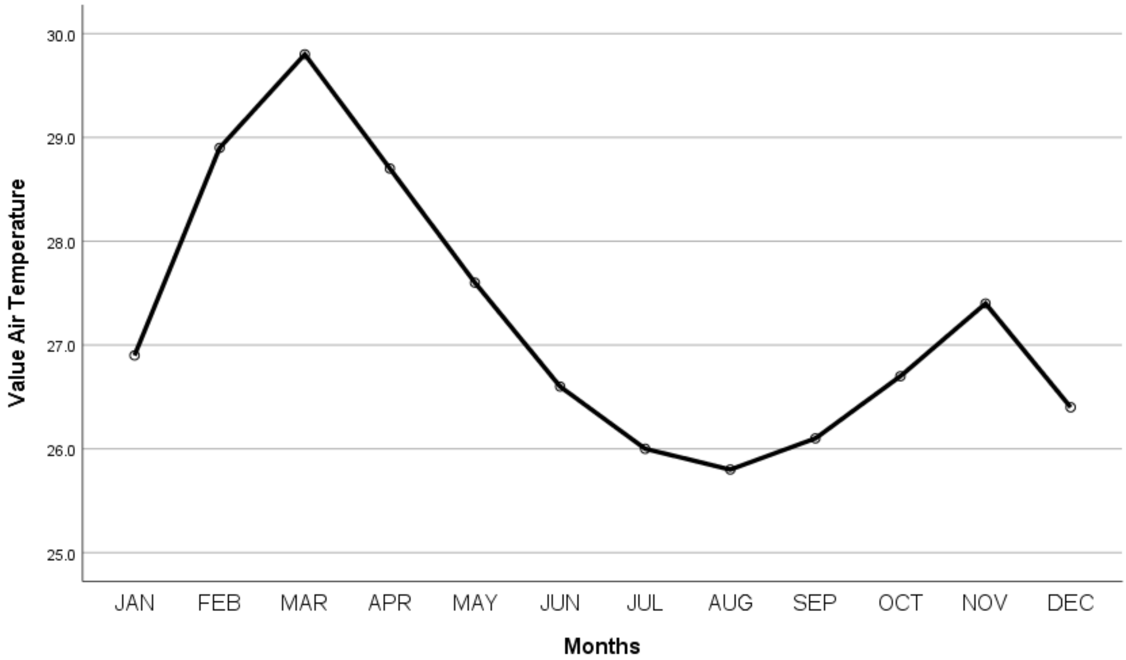
Appendix A: The Average Monthly Air Temperature in Enugu Urban



Appendix B: The Average Seasonal Air Temperature in Enugu Urban