Lafia Journal of Scientific & Industrial Research (LJSIR), Vol. 3(2), 2025
p-ISSN: 3026 – 9288 e-ISSN: 3027 – 1800 pages: 148 – 154
https://lafiascijournals.org.ng/index.php/ljsir/index ⇒ Published by the Faculty of Science,
Federal University of Lafia, Nasarawa State, Nigeria

Low-Cost Weather Station Assessment of Urban Heat Island Compared with ERA5 Reanalysis Data

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Abstract

Rapidly urbanizing regions usually experience urban heat islands with the attendant environmental and public health challenges. This study has used a low-cost LILYGO T-SIM7000G board with BME280 as a sensor to assess the UHI Index and compare such results with those obtained from the Copernicus ERA5-Land reanalysis data. The result shows a bias of about 1.36 in the UHI Index against the ERA5-Land data; this bias can be mitigated by applying a corrective offset. It was also observed that the ambient temperature in Lafia city has been consistently increasing between the years 1980 and 2024 by about 0.017^oC per year, with the highest increase recorded in the year 2024. The highest diurnal value of the UHI Index was observed around 1500 *hours*, while the lowest nighttime value was observed at around 0600 *hours*; this finding agrees with results as observed in other studies. This study has shown the importance of adopting low-cost components in monitoring environmental variables such as the UHI Index in low-income areas of the world where funding may pose problems.

Keywords: Urban heat island, climate, temperature, LILYGO T-SIM7000G, ERA5-Land, weather station

Article History
Submitted
June 28, 2025
Revised
October 10, 2025
First Published Online
October 14, 2025

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doi.org/10.62050/ljsir2025.v3n2.666

Introduction

Urban heat island (UHI) refers to a phenomenon where an urban area experiences a considerably higher air temperature than the adjacent rural area. This phenomenon is due to anthropogenic activities such as land use changes, increases in human population, and changes in the physical characteristics of the urban space. There is growing concern about UHI coupled with the globally experienced climate change; the increase in urban temperature has resulted in health risk vulnerabilities and damage to natural environments [1–3].

As urbanization increases and its effects on local climates impact human health, energy consumption, and urban planning, research on low-cost weather stations and ERA5 reanalysis data in urban heat island (UHI) studies has become a crucial area of inquiry [4, 5]. Many changes have occurred since the first urban heat island was observed in the 19th century, from the use of satellites for remote sensing to sophisticated computer numerical modelling [6, 7]. In-depth microclimatic assessments in urban areas are now feasible with the use of newly innovated low-cost sensors and development boards, thereby significantly increasing the spatio-temporal ability for data collection [8, 9]. Understanding and reducing the effects of UHI is essential for sustainable urban development and climate resilience, as the proportion of people living in cities is expected to increase to 70% by 2050 [6, 10].

The structure of the urban environment significantly contributes to the observed urban heat island; typically, Locke [2] observed that 20% of solar radiation is reflected by the urban surfaces while the remaining 80% is absorbed, leading to a temperature increase. If a more reflective material is used, 50% of the solar insolation could have been reflected, hence leading to air temperature reduction [2, 11]; among other strategies that could be employed to mitigate the effect of urban heat islands in cities are the use of cool roofs and reflective pavements. Studies in Europe have established that there is greater heat stress experienced in larger cities with the attendant higher ambient temperature at the city centers; for example, it was observed that city centers in London and Paris have a 4°C increase in ambient temperature during the night as compared to adjacent rural areas [1].

Densely populated urban regions have significant health implications due to the effect of urban heat island, for instance, in the United States of America, urban residence account for nearly 80% of the total population and the ambient temperature in these urban areas has been observed to increase by about 8^oF when compared with the adjacent rural areas [2]. It has also been shown that mortality rate per degree rise in ambient temperature during the heat waves increased by almost

2.5% [2]. This effects of urban heat island significantly affects the elderly, infants and vulnerable individuals more; hence, resulting in urban heat island as a special public health problem.

It is the aim of this study to explore the usability of low-cost and accessible development boards and sensors for the assessment of urban heat islands in sprawling urban environments.

Materials and Methods

The LILYGO T-SIM7000G is an economical ESP32 development board, shown in Fig. 1; capable of internet connectivity via a SIM card, supporting GPS, GPRS, and LTE CAT-M1 protocols. The board can be outfitted with a solar-powered supply, allowing it to gather atmospheric data in a remote area, with the information being transmitted to the cloud in real-time while the on-board SD card retains the obtained data locally. This study uses BME280, as illustrated in Fig. 2, to gather ambient temperature, air pressure, and relative humidity data from urban and rural sites in Lafia and its surroundings.

The board connectors and programming for the LILYGO T-SIM7000G board are available on Randomnerd's website at https://randomnerdtutorials.com/lilygo-t-sim7000g-esp32-lte-gprs-gps/

Figure 1: LILYGO T-SIM7000G development board

Figure 2: BME280 sensor (for temperature, pressure and relative humidity)

Lafia is the capital city of Nasarawa State, within the north-central region of Nigeria. Lafia, as a region of interest (roi), for this study, is shown in Fig. 3. The region of interest is situated within latitudes 8.5500 ^oE and 8.4658 ^oE as well as longitude 8.6169 ^oN and 8.4661 ^oN, with a total land area of 155 km^2. The city became the capital city of Nasarawa State in 1996 upon the creation of Nasarawa State. Before the creation of Nasarawa State, Lafia was a rural area with a human population of less than 12,000 [12].

Climatologically, Lafia is classified as *Aw* on a Köppen climate classification, within the tropical savannah [13]. The city has an average ambient temperature of 26.7^oC, total annual rainfall of 1,645 *mm* with about 251 rainy days, and an average relative humidity of about 75% [13]. This evidence shows that Lafia and its environs are a hot and humid region with distinct wet and dry seasons.

The ERA5-Land daily average temperature data were obtained from a computer model reanalysis available at https://app.climateengine.org/climateEnging. The ERA5-Land data has a resolution of 11.1 *km* (i.e., 0.125^o by 0.125^o) with temperature data calculated at a height of 2 *metre* above the ground [14].

The Urban Heat Island (UHI) Index was calculated using the expression in Equation 1:

$$UHI_{index} = \frac{T - T_{rural}}{T_{rural}} \quad 1$$

where T represents the air temperature, and the average temperature of the adjacent rural area is denoted as T_{rural}.

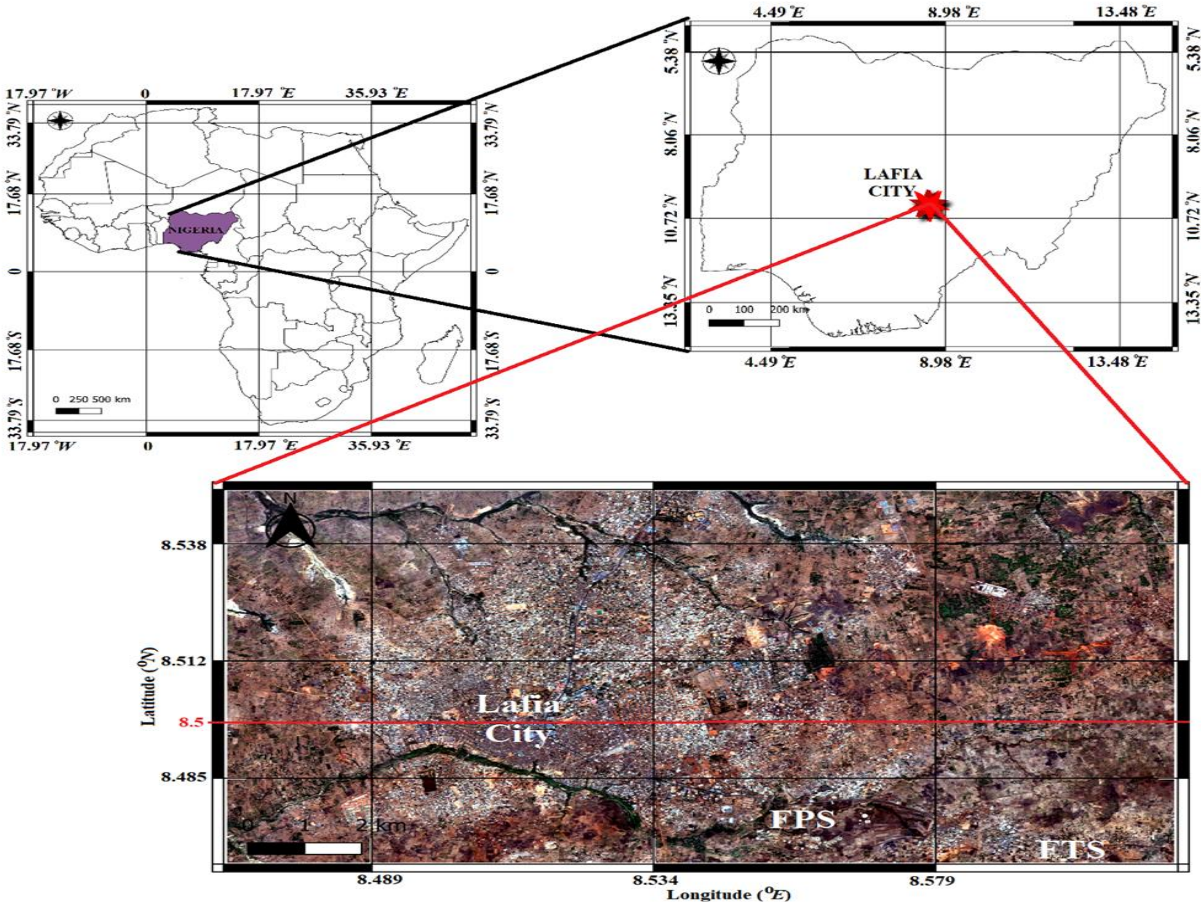

Figure 3: Map of the study area (weather stations at Lafia city and at FPS)

Results and Discussion

Ambient air temperature trend

Figure 4 shows the annual average 2-m air temperature in Lafia from the year 1980 to 2024, based on the ERA5-Land data. In Fig. 4, the Sen's slope, which is a non-parametric estimate known for its robustness against outliers and data irregularities, is found to be approximately 0.017^oC/*year*. The Mann-Kendall Tau-value was found to be +0.4758, while the Mann-Kendall p-value was found to be 0.000004 (< 0.05). The above results show that the mean annual air temperature in Lafia has been significantly and consistently increasing at a rate of about 0.017^oC/*year*, which agrees with increasing temperatures in other sprawling urban areas, such as those observed by Iamtrakul *et al.* [15], Nasar-u-Minallah *et al.* [16] and Zhang *et al.* [17].

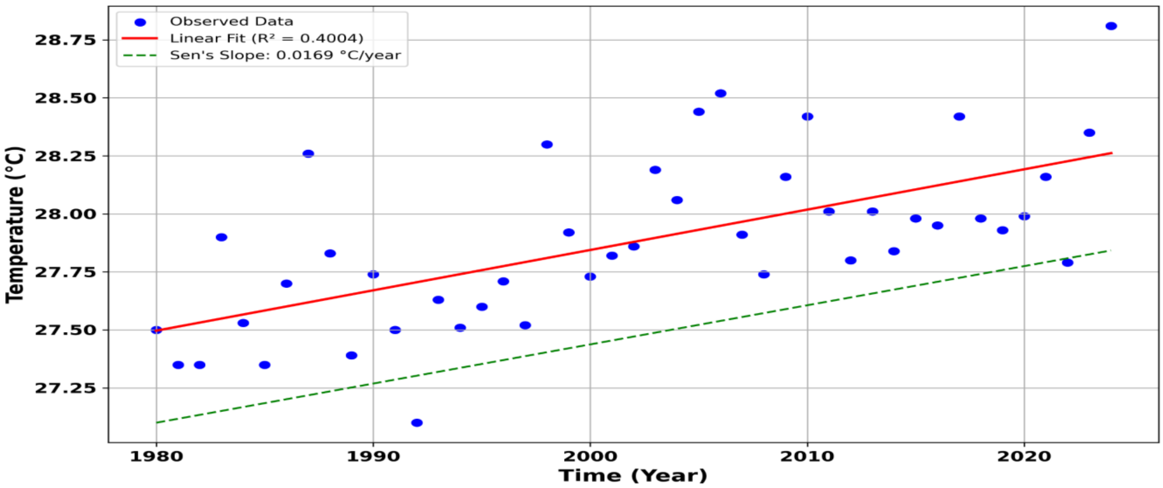

Figure 4: Plot of mean annual 2-*m* air temperature for Lafia

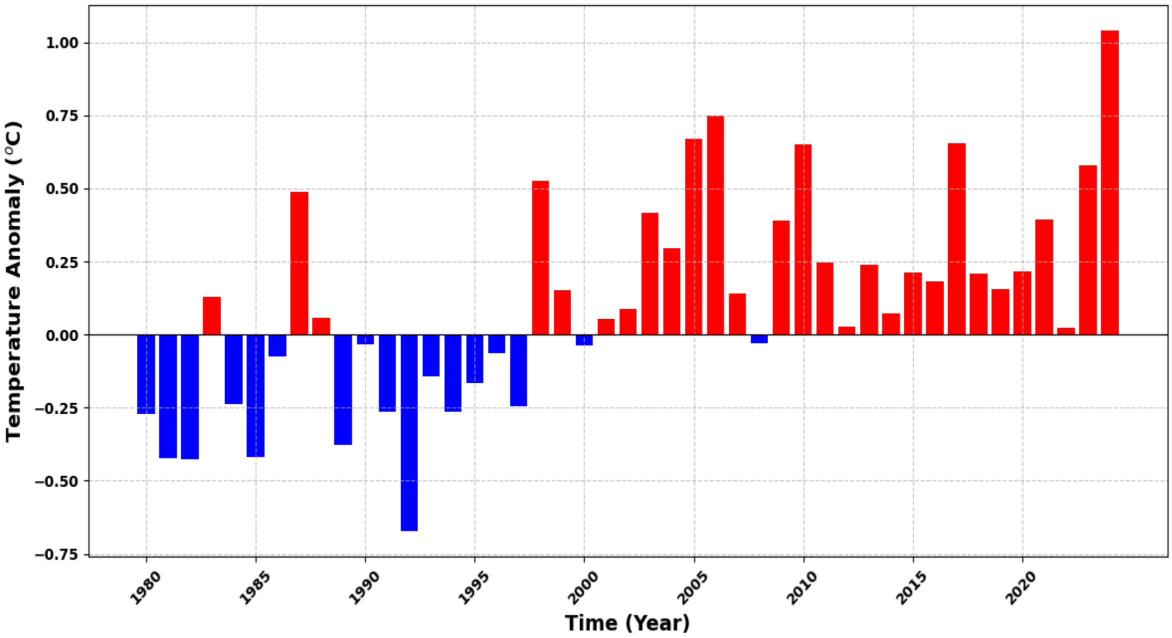

Figure 5: Land surface annual mean temperature anomaly in Lafia city between the year 1980 and 2024 (baseline: 1980-2009 average)

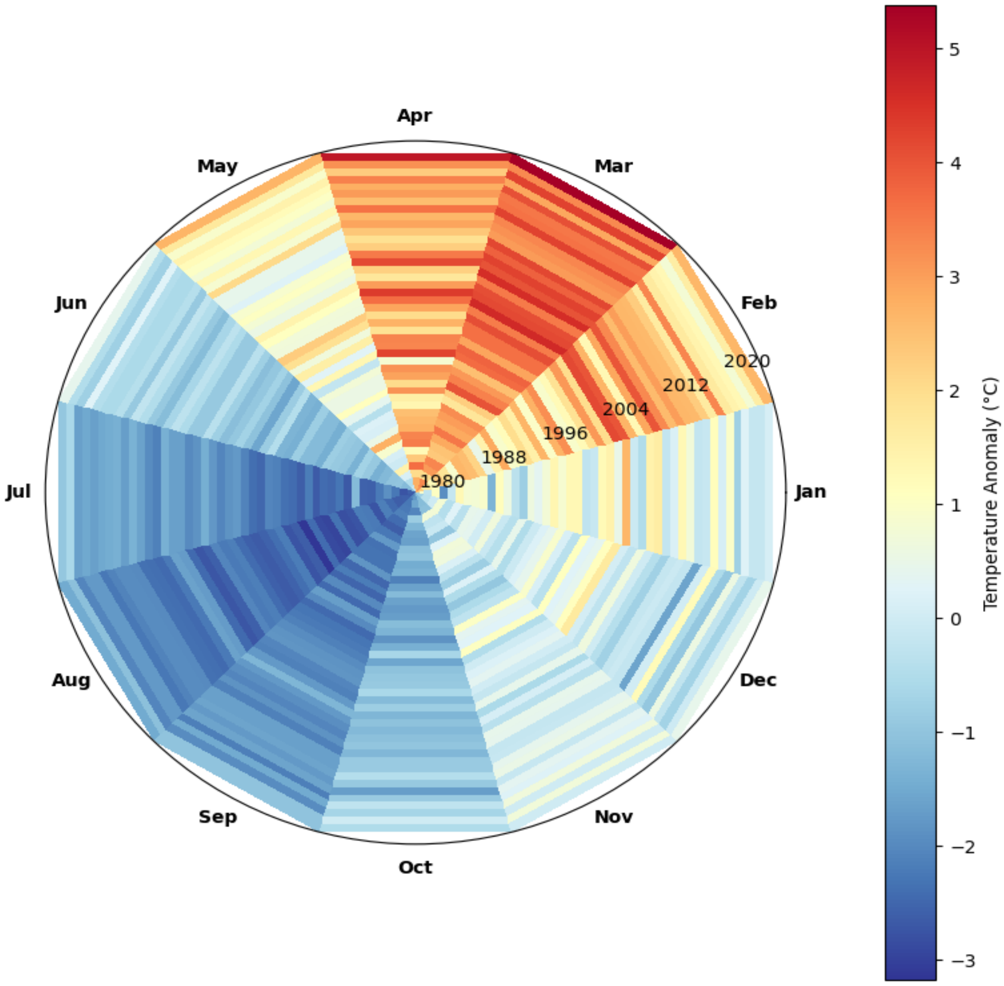

Figure 6: Land surface monthly mean temperature anomaly in Lafia city between the year 1980 and 2024 (baseline: 1980-2009 average)

The annual temperature anomaly against the 1980-2009 baseline local average of 27.77^oC is shown in Fig. 5, while Fig. 6 shows the anomaly every month. In Fig. 5, the consistent increase in temperature in Lafia can be well observed, with the year 2024 having the highest temperature when compared to the 1980-2009 baseline average. Fig. 6 shows that the highest monthly temperature in Lafia is usually during the month of March, while the coolest month is the month of August, but the consistent increase over the years in Lafia air temperature can also be observed.

The above results indicate that the air temperature in Lafia has been increasing over time due to urban developments and population growth in the city; as the capital city of Nasarawa State, Lafia experiences continuous urban development. Therefore, it is necessary to investigate the urban heating effect, commonly referred to as an urban heat island that has been experienced by Lafia.

Urban heat island (UHI)

Figure 7 displays the calculated Urban Heat Island (UHI) Index using ERA5-Land and constructed weather station data. The temporal pattern of the two results closely aligns, but the values greatly differ, with ERA5-Land giving negative values while the in-situ weather station is in the positive range.

The coefficient of determination (R^2) between the two results was found to be -111.41, the root mean square error (RMSE) was found to be 1.37, while the mean bias error (MBE) was found to be -1.36. These statistics indicate that there is a significant systematic bias in the values of the UHI Index obtained from ERA5-Land relative to those obtained from the in-situ weather station. The observed bias is due mainly to the fact that the ERA5-Land data is on a pixel resolution of 11.1 *km*, that is, the data is averaged over a surface area of 123.21 km^2, as compared with the in-situ data that is on a point location within the city of Lafia and at a point location at the outskirts of the city of Lafia. By offsetting the ERA5-Land data and adding 1.36 to each data point, we can reduce the observed bias in the data sets.

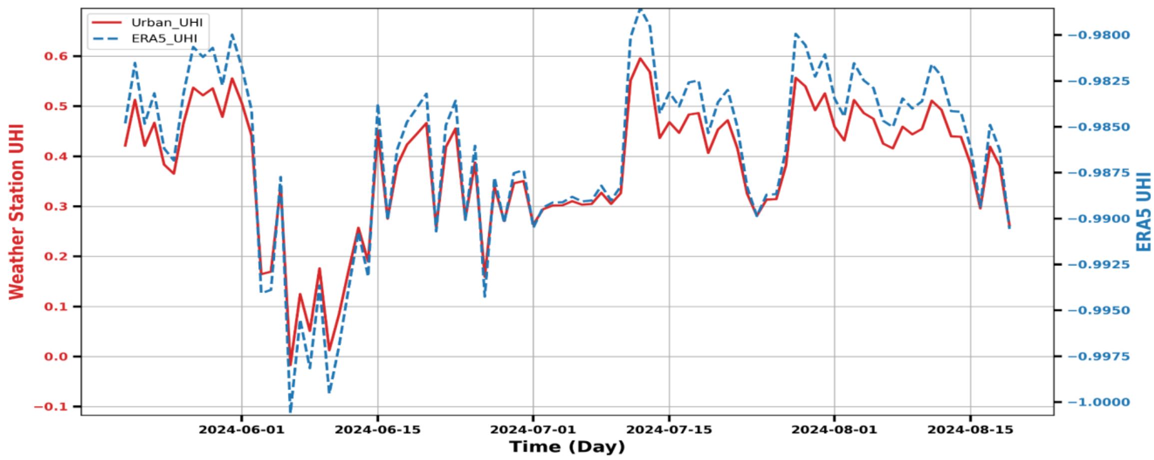

Figure 7: Daily urban heat island, through May to August, 2024, from ERA5-Land and constructed weather station data

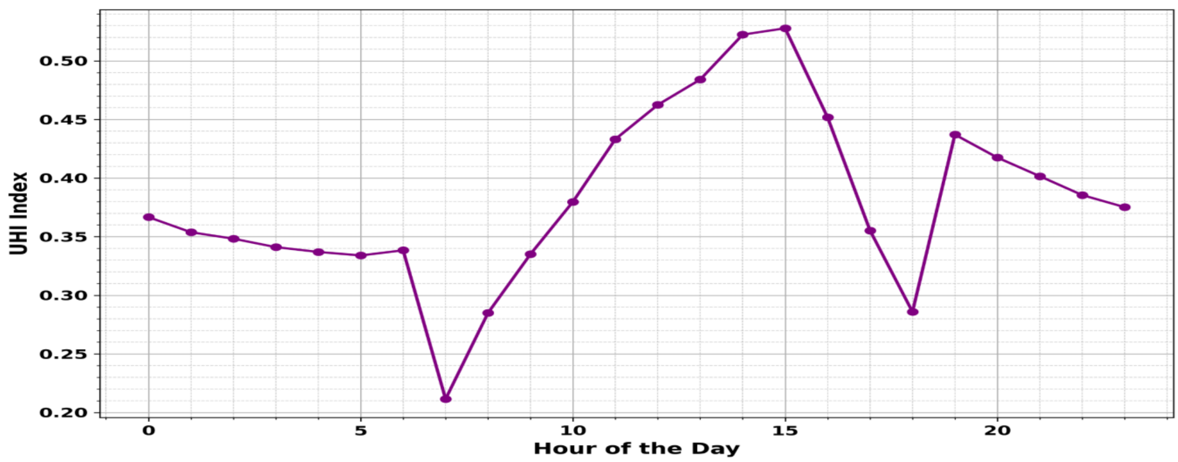

Figure 8: Daily hourly mean of UHI index between May 20 and August 19, 2024

Daily variation of UHI

Figure 8 shows the daily average of the UHI index, derived from the in-situ weather station data, for the observation period of May 20 to August 19, 2024. The diurnal (0700 to 1800 *hour*) values of UHI index can be observed to be higher than the nighttime (1900 to 0600 *hour*) values of UHI index and it was found that the diurnal average is higher than the nighttime average by 0.0248; this is in agreement with observations of other researchers such as, Usman *et al.* [18], Zargari *et al.* [19], Xu *et al.* [20], Zhou *et al.* [21], and Nichol [22].

It can be observed in Figure 8 that the Lafia urban area typically experienced the lowest UHI Index during the coolest hour of the day, around 0600 *hours*, while the highest UHI Index is usually around the hottest part of the day at 1500 *hours*.

Conclusion

This study has used a low-cost LILYGO T-SIM7000G module with BME280 as a sensor and data from Copernicus ERA5-Land to assess the Urban Heat Island (UHI) effect in Lafia, Nasarawa State, Nigeria. A significant and consistent increase in annual temperature from 1980 to 2024 was revealed in the study for the urban area of Lafia city, with the higher diurnal urban heat island intensity at around 1500 *hours*.

Differences were observed in the UHI index obtained from the in-situ weather station and that from the ERA5-Land data due mainly to the coarse resolution of the ERA5-Land data as compared with the point location data of the in-situ weather station, but such differences were shown to be reduced with the proper bias adjustment.

This study's results support the idea that climate change caused by human activities affects local temperature, which in turn leads to changes in the microclimate of urban areas. The use of low-cost technology to monitor the urban microclimate was demonstrated, and such an instrument is recommended for proper monitoring, especially in places where funding is an issue.

It is recommended that future research leverage this study to further study and expand the use of the low-cost instruments for monitoring of local microclimate.

Conflict of interest: The authors declare that there is no conflict of interest.

Acknowledgement: The Tertiary Education Trust Fund (TETFund) of Nigeria supported this research with a 2025 Institutional-Based Research (IBR) grant. Hence, the authors wish to thank TETFund for providing funding for this research.

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Citing this Article

Musa, A., Adewumi, T., Muhammad, S., & Abimbola, O. J. (2025). Low-cost weather station assessment of urban heat island compared with ERA5 reanalysis data. *Lafia Journal of Scientific and Industrial Research, 3*(2), 148 – 154. https://doi.org/10.62050/ljsir2025.v3n2.666