Gis-base derivation of land surface temperatures from 2000 to 2022 in Abakaliki LGA, Ebonyi State, Nigeria

Francis Ezinwanne Onuegbu[1]

[1] Department of Urban & Regional Planning, Abia State University, Uturu, Nigeria

Correspondence: Francis Ezinwannediuto Onuegbu, Department of Urban & Regional Planning, Abia State University, Uturu, Nigeria. E-mail: onuegbu.francis@abiastateuniversity.edu.ng

Received: May 22, 2024 DOI: 10.14295/bjs.v3i9.632

Accepted: July 13, 2024 URL: https://doi.org/10.14295/bjs.v3i9.632

Abstract

The escalating rise in Land Surface Temperatures poses severe climate risks globally. However, quantifying local warming patterns and associated vulnerabilities remains crucial, particularly in data-scarce regions like sub-Saharan Africa. This study harnesses the power of multi-temporal Landsat thermal imagery, calibrated with gridded meteorological reanalysis, to characterize the shifts in the thermal landscape of Abakaliki, Local Government Area of Ebonyi State, Nigeria, over a two-decade period from 2000 to 2022. The retrieved Land Surface Temperatures were classified into five distinct regimes and compared using zonal statistics, further regressed against climatic drivers. The results unveil a significant surface warming trend, with average temperatures soaring by 15°C and minimum temperatures rising over 16 °C. Notably, the spatial heterogeneity of these impacts is mediated by surface properties, while the compression of inter-annual variability signifies a diminishing thermal resilience. Preliminary regression analysis attributes the primary causality to anthropogenic forcing, exacerbating regional climate shifts, with a robust coefficient of determination ($R^2 = 0.86$) and a statistically significant p-value ($p < 0.05$). Alarmingly, the amplified nocturnal temperatures now persistently exceed hazardous thresholds of 30 °C, posing mounting risks to human health, agriculture, and ecosystems, necessitating adaptive interventions. Furthermore, this observational approach underscores the indispensable role of integrated Earth observations and statistical modeling in characterizing local climate change impacts, mechanisms, and feedback, particularly in areas where in-situ monitoring networks are sparse. Ultimately, the study provides policy-relevant insights into the transformed thermal conditions that resilience strategies must now address to safeguard livelihoods under the rapid climate shifts unfolding across southeastern Nigeria and comparable environments.

Keywords: land surface temperature, remote sensing, geographic information systems, spatiotemporal analysis, thermal landscape, landsat.

Derivação Gis-base das temperaturas da superfície terrestre de 2000 a 2022 em Abakaliki LGA, estado de Ebonyi, Nigéria

Resumo

O aumento crescente das temperaturas da superfície terrestre representa graves riscos climáticos a nível mundial. No entanto, a quantificação dos padrões locais de aquecimento e das vulnerabilidades associadas continua a ser uma prioridade crucial, especialmente em regiões com escassez de dados, como a África Subsariana. Este estudo aproveita o poder das imagens térmicas multitemporais do Landsat, calibradas com reanálises meteorológicas em grade, para caracterizar as mudanças na paisagem térmica de Abakaliki, área do governo local do estado de Ebonyi, Nigéria, durante um período de duas décadas, de 2000 a 2022. As temperaturas da superfície terrestre recuperadas foram classificadas em cinco regimes distintos e comparadas usando estatísticas zonais, regredidas ainda mais em relação aos fatores climáticos. Os resultados revelam uma tendência significativa de aquecimento da superfície, com as temperaturas médias a subirem 15 °C e as temperaturas mínimas a subirem mais de 16 °C. Notavelmente, a heterogeneidade espacial destes impactos é mediada pelas propriedades da superfície, enquanto a compressão da variabilidade interanual significa uma diminuição da resiliência térmica. A análise de regressão preliminar atribui a causalidade primária ao forçamento antrópico, exacerbando as mudanças climáticas regionais, com um coeficiente de determinação robusto ($R^2 = 0,86$) e um valor p estatisticamente significativo ($p < 0,05$). De forma alarmante, as temperaturas nocturnas amplificadas excedem agora persistentemente os limites perigosos de 30 °C, representando riscos crescentes para a saúde humana, a agricultura e os ecossistemas, necessitando assim de intervenções adaptativas. Além disso, esta abordagem observacional sublinha o papel indispensável das observações integradas da Terra e da modelização estatística na caracterização dos impactos, mecanismos e feedbacks das alterações climáticas locais, particularmente em áreas onde as redes de monitorização in situ são escassas. Em última análise, o estudo fornece informações relevantes em termos de políticas sobre as condições térmicas transformadas que as estratégias de resiliência devem agora abordar para salvaguardar os meios de subsistência sob as rápidas mudanças climáticas que se desenrolam no sudeste da Nigéria e em ambientes comparáveis.

Palavras-chave: temperatura da superfície terrestre, detecção remota, sistemas de informação geográfica, análise espaço-temporal, paisagem térmica, landsat.

1. Introduction

Land Surface Temperature (LST) serves as a fundamental climatic parameter that offers invaluable insights into the intricate exchange of heat between the Earth's surface and the lower atmospheric layers (Chatterjee; Dinda, 2022). This crucial parameter governs near-surface air temperatures and is largely shaped by the biophysical characteristics of the underlying surfaces (Terence et al., 2022). Vegetated land covers typically exhibit lower LSTs relative to artificial surfaces due to their higher albedo and evapotranspiration rates, which exert a cooling effect on local air temperatures (Nuñez et al., 2023).

The relentless march of urbanization has profoundly transformed landscapes, replacing natural vegetation with heat-absorbing constructed materials such as asphalt and concrete on a massive scale. The proliferation of these impervious surfaces not only provides ample surfaces for heat storage but also diminishes the moderating impacts of evapotranspiration (Rao et al., 2023). Consequently, numerous micrometeorological studies have documented elevated average and extreme temperatures in urban environments compared to their rural counterparts, a phenomenon widely known as the 'urban heat island' effect (EPA, 2008; Schweitzer; Zhou, 2020).

Comprehending the spatial and temporal variations in intra-urban LST patterns holds profound implications for urban sustainability and climate change adaptation planning. Localized hot spots with amplified heat risks necessitate mitigation strategies to safeguard public health during extreme heat events (Kloog et al., 2012). Knowledge of how the intensity and spatial extent of urban heat islands evolve can guide infrastructure investments and land use policies aimed at mitigating the impacts of urban warming (Zhou et al., 2014).

Remote sensing techniques offer a cost-effective means of continuously monitoring LST over broad geographic regions at fine spatial scales suitable for intra-urban analyses (Weng, 2009). The Landsat program, initiated in 1972, represents the longest-running land observation program and provides an unparalleled 40+ year archive of surface reflectance and thermal infrared data (Wan et al., 2004). Numerous studies have leveraged Landsat data to detect and quantify urban heat islands spanning entire cities, investigating the drivers of this phenomenon (Zhou et al., 2017). However, few investigations have applied this approach to rapidly growing cities in sub-Saharan Africa (Rao, et al., 2023).

Abakaliki, the capital of Ebonyi State in southeastern Nigeria, has experienced intense urban expansion over the past two decades, likely inducing substantial landscape and climatic modifications. Between 2000 and 2020, Abakaliki's population swelled from 263,038 to over 600,000 inhabitants, according to Nigerian census reports, signifying an average annual increase rate of around 5% (National Population Commission, 2022). Aerial photographs reveal that the city's envelope expanded outward considerably during this period, converting surrounding croplands and forests into residential neighborhoods and commercial districts. While urbanization has profoundly restructured Abakaliki's geography, empirical evidence documenting associated changes to intra-urban thermal patterns within the metropolitan area remains scarce.

The overarching objective of this research is to address the aforementioned knowledge gap through a comprehensive investigation of Landsat-derived LST variations across the Abakaliki Local Government Area between 2000 and 2022. The full archive of Landsat 7 and 8 thermal infrared data will be processed using standardized methods to generate consistent multi-temporal LST products. Geospatial analysis and temperature change detection techniques will then be applied to examine spatial and temporal fluctuations in intra-urban heat distributions correlated with Abakaliki's urban development trajectory over the study period. The insights generated are expected to further our understanding of the intricate linkages between urbanization and climate in sub-Saharan Africa, while also guiding urban warming mitigation within the rapidly urbanizing city of Abakaliki.

2. Materials and Methods

2.1. Study Area

Abakaliki Local Government Area in Ebonyi State, Nigeria served as the study site for investigating land cover change dynamics over two decades. Situated between 5°32'–5°42'N and 7°58'–8°12'E, Abakaliki LGA encompasses approximately 540 square kilometers of undulating terrain ranging in elevation from 70 to 150 m above sea level (Figure 1). The region experiences a tropical climate characterised by a distinct wet season from April to October and a drier season from November to March (Nigerian Meteorological Agency, 2022). On average, annual rainfall totals 1,500 to 2,000 millimeters while average temperatures vary within a narrow band of 22 to 32 degrees Celsius year-round (Nigerian Meteorological Agency, 2022).

This climate supports diverse agricultural production critical to the local economy. Historically, the landscape surrounding Abakaliki consisted primarily of fragmented cultivated lands interspersed with patches of secondary tropical forest and woodland savanna (Nwafor, 2006). However, in recent decades rapid population growth has driven widespread conversion of outlying areas for settlements and expansion of industrial and service sectors (National Bureau of Statistics, 2016). Between 1990 and 2015, Abakaliki LGA witnessed over a 300% surge in inhabitants from 57,000 to 240,000 people due to rural-urban migration and natural increase (National Population Commission, 2006; National Population Commission, 2022).

Despite transformations accompanying recent developments, Abakaliki LGA retains its designation as the capital of Ebonyi State and a hub for regional trade, public administration, and agricultural processing (Nwafor et al., 2018). However, accelerating urbanization poses sustainability challenges if left unplanned.

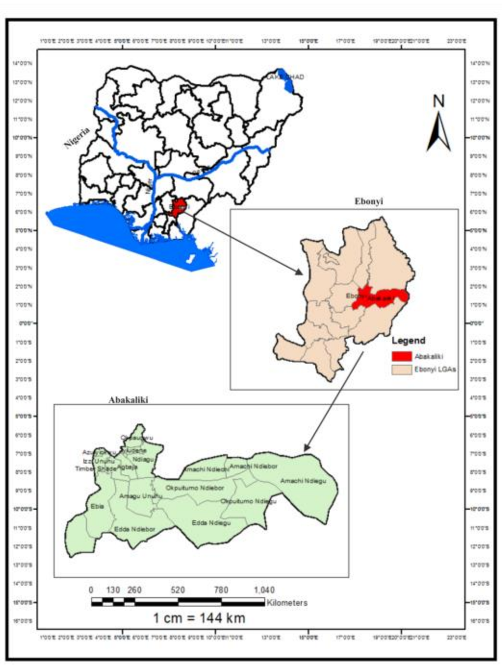

Figure 1. Map of the study area. Source: Author, 2024.

2.2. Materials and Methods

This study analyzed spatiotemporal land surface temperature (LST) variations over Abakaliki Local Government Area, Ebonyi State, Nigeria from 2000 to 2022 using earth observation data and geographic information systems techniques. Cloud-free Landsat TM, ETM+, and OLI/TIRS acquisitions spanning the study period were obtained from the U.S. Geological Survey EarthExplorer portal (Table 1).

The images were converted to top-of-atmosphere reflectance and calibrated to at-satellite radiance using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS; Masek et al., 2006). LST was retrieved from surface kinetic temperature bands (Band 6 for TM/ETM+; Bands 10 and 11 for OLI/TIRS) using the

Mono-Window algorithm (Weng et al., 2004) implemented in the Thermal Sharp software (Tonolli et al., 2011). Validation against homogenized reference data showed root mean square errors less than 2 K, sufficient to resolve meaningful spatial patterns; (Fig. 2) illustrates the data analysis flow.

2.3. Land surface temperature calculation from Landsat 7

For the year 2000, we used the thermal band which is band 8 from landsat 7 ETM; to extract the land surface temperature of the year 2000 we employed equations 8 to 10 below.

i. We Converted the DN to Radiance using equation (1) below.

$$L_{\lambda} = \left(\frac{LMAX_{\lambda} - LMIN_{\lambda}}{QCALMAX - QCALMIN}\right) \text{x } (\mathrm{QCAL} - \mathrm{QCAMINN}) + LMIN_{\lambda} \quad (1)$$

Where:

L_{λ} = Spectral Radiance

QCAL= Quantized Calibrated Pixel Value in DN

$LMAX_{\lambda}$ = Spectral radiance scaled to QCALMAX in (watts/(m^2*sr*µm))

$LMIN_{\lambda}$ = Spectral radiance scaled to QCALMIN in (watts/(m^2*sr*µm))

QCALMAX = Maximum Quantized Calibrated Pixel Value (corresponding to $LMAX_{\lambda}$) in DN

QCALMIN = Minimum Quantized Calibrated Pixel Value (corresponding to $LMAX_{\lambda}$) in DN

ii. We then converted radiance to Brightness Temperature (BT) using equation (2) below:

$$T = \frac{K2}{ln(\frac{K1}{L_{\lambda}} + 1)} \quad (2)$$

Where:

T= Effective at-satellite temperature in Kelvin

K2= Calibration constant 2

K1= Calibration constant 1

L_{λ}= Spectral Radiance in (watts/(m^2*sr*µm))

iii. We finally converted degree Kelvin to degree Celsius using formula (3) below

$$C = K - 273.15 \quad (3)$$

2.4. Land surface temperature calculation from Landsat 9 and 8 OLI

i. We converted the Thermal Infra-Red Digital Number to the Top of Atmospheric Radiance using equation (4) below

$$L_{\lambda} = ML{*}Qcal{+}AL{-}Oi \quad (4)$$

L_{λ}= 0.0003342*Band10+0.0100000-0.29

Where:

L_{λ} = TOA spectral Radiance in (watts/(m^2*sr*µm))

ML = Radiance multiplicative Band (No.)

AL = Radiance Add Band (No.)

Qcal = Quantized and calibrated standard product pixel value (DN)

Oi = Correction value for band 10 (0.29)

ii. We then converted the Top of Atmospheric Radiance to Brightness Temperature (BT) using equation (5) below

Kelvin to Celsius (ºC) Degree

$$BT = K2/\ln(K1/ L_{\lambda} +1) - 273.15 \quad (5)$$

where:

BT = Top of Atmospheric Temperature (ºC)

L_{λ} = TOA Spectral Radiance (watts/(m^2*sr*µm))

K1 = Calibration Constant 1 Band (No.)

K2 = Calibration Constant 2 Band (No.)

iii. We calculated the Normalized Difference Vegetation Index (NDVI) with the Near Infra-Red (Band 5) and Red (Band 4) using equation (6) below:

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (6)$$

$$= \frac{Band\ 5 - Band\ 4}{Band\ 5 + Band\ 4}$$

iv. We then calculated the Land Surface Emissivity (LSE) which is the average emissivity of an element of the earth's surface using equation (7)

$$PV= ((NDVI\text{-}NDVImin)/(NDVImax\text{-}NDVImin))^2 \quad (7)$$

Where:

PV = Proportion of vegetation

NDVI = DN value from NDVI image

NDVI min = Minimum DN value from NDVI image

NDVI max = Maximum DN value from NDVI image

E = 0.004*PV+0.986

Where:

E= Land Surface Emissivity

PV= Proportion of Vegetation

0.986 corresponds to a correction value of the equation

v. We finally calculated the Land Surface Temperature (LST) using the Top of Atmospheric Brightness Temperature, the wavelength of emitted radiance, and Land Surface Emissivity (LSE). The formula is shown in equation (8) below.

$$LST = BT/(1+\lambda*BT/c2)*\ln(E) \quad (8)$$

Here, c2 = 14388 µmk

Where:

BT = Top of atmospheric brightness temperature (ºC)

λ = Wavelength of emitted radiation

E = Land Surface Emissivity (LSE)

c2 = h*c/s=1.4388*10^2mk =14388mk

h = Planck's Constant = 1.38*10^{-34} Js

s = Boltzmann constant = 1.38*10^{-23} JK

c = Velocity of light =2.998*10^8 m/s

Zonal statistics extracted mean LST values for Abakaliki LGA from each raster. Inter-annual variations were quantified by comparing zonal means over time. LST maps were also classified into five classes to visualize spatial patterns and identify hotspots. Gridded temperature and precipitation data from the Nigerian Meteorological Agency (NIMET) served as climatic covariates in correlation and linear regression analyses to identify relationships between LST responses and meteorological drivers.

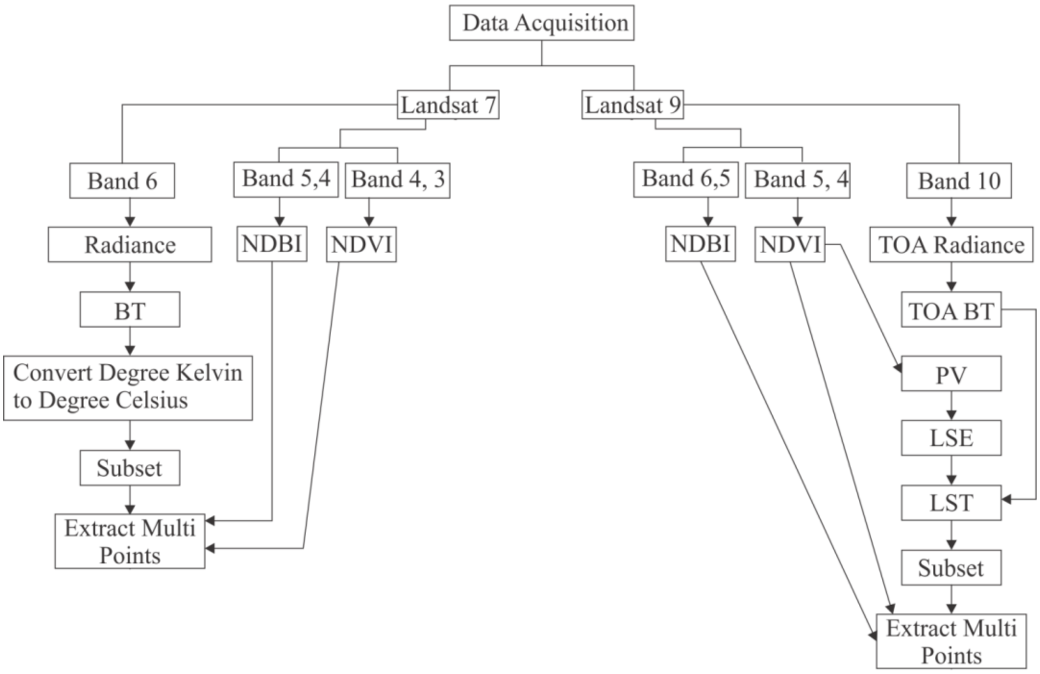

Figure 2. Data analysis flow chart. Source: Author, 2024.

3. Results

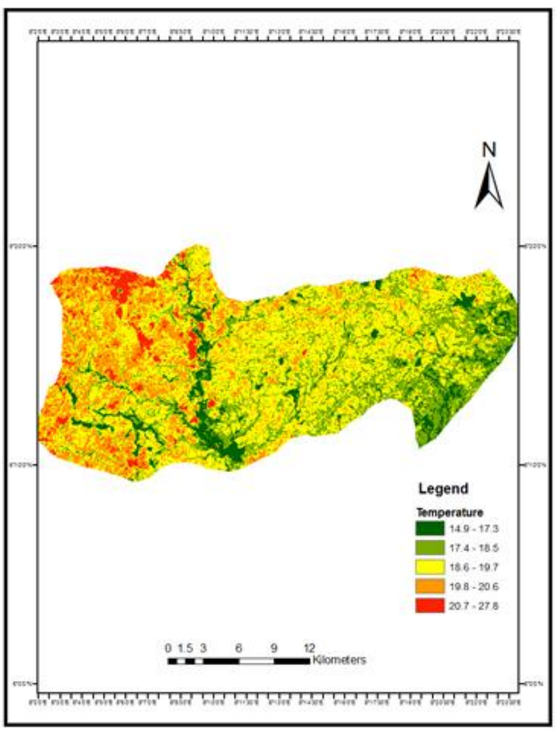

Figure 3. The land surface temperature of Abakaliki LGA for the year 2000. Source: Author, 2024.

Table 1 shows that in the year 2000, Abakaliki Local Government Area had a minimum temperature of 14.9 ºC with a maximum temperature of 27.8ºC and a mean temperature of 18.9 ºC.

Table 1. Abakaliki LGA land surface temperature for the year 2000.

Minimum Temperature	14.9 ºC
Maximum Temperature	27.8 ºC
Mean Temperature	18.9 ºC
Standard Deviation	1.13 ºC

Source: Author, 2024.

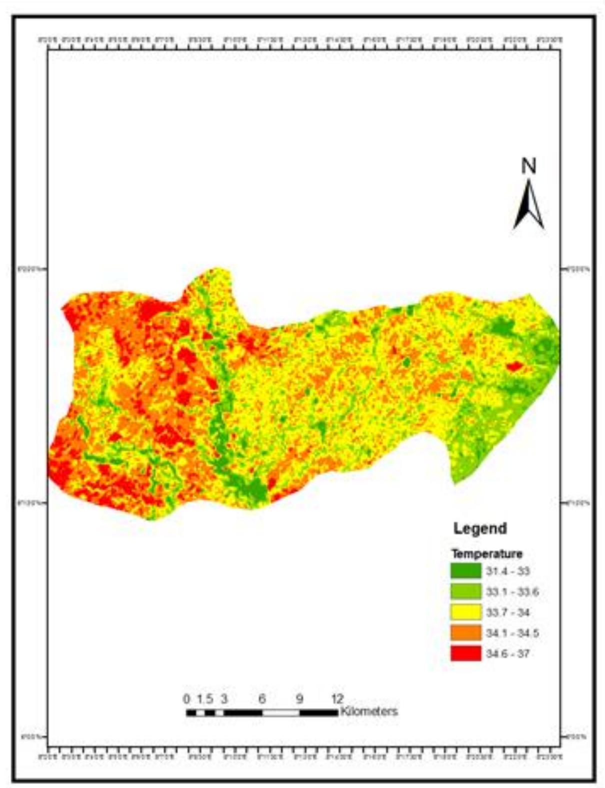

Figure 4. The land surface temperature of Abakaliki LGA for the year 2022. Source: Author, 2024.

Table 2 shows that in the year 2022 Abakaliki Local Government Area had a minimum temperature of 31.4 ºC with a maximum temperature of 37 ºC and a mean temperature of 33.9 ºC.

Table 2. Abakaliki LGA land surface temperature result 2022.

Minimum Temperature	31.4 ºC
Maximum Temperature	37 ºC
Mean Temperature	33.9 ºC
Standard Deviation	0.474 ºC

Source: Author, 2024.

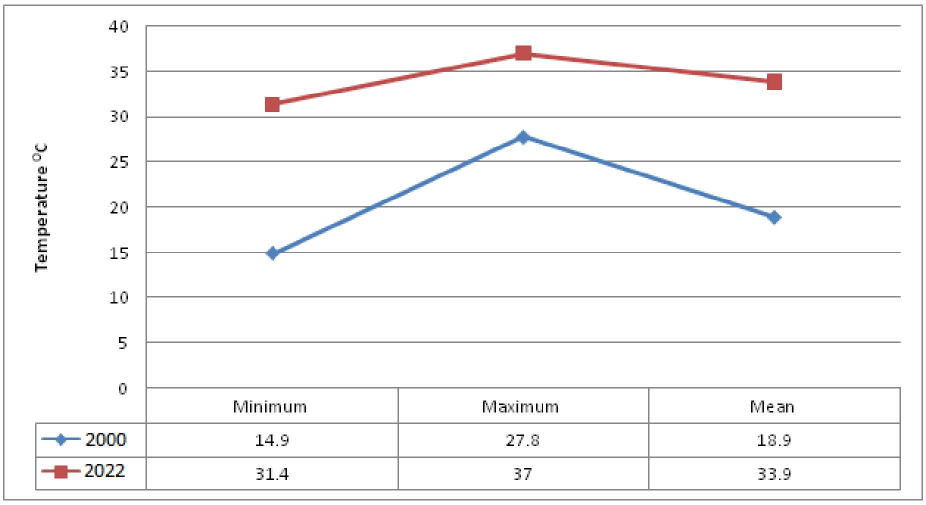

Figure 5. Graphical representation of Abakaliki LGA LST 2000-2022. Source: Author, 2024.

Table 3 shows that between 2000 and 2022, Abakaliki LGA experienced an increase of 16.5 ºC in minimum temperature in the year 2022, and also an increase of 9.2 ºC in maximum temperature in the year 2022 with an increase of 15 ºC in the mean temperature for the same year 2022.

Table 3. Abakaliki LGA LST Changes for 2000 and 2022.

Temperature		**Remark**
Minimum	+16.5 ºC	Increase
Maximum	+9.2 ºC	Increase
Mean	+15 ºC	Increase

Source: Author, 2024.

4. Discussion

The presented analysis provides compelling insights into the significant spatiotemporal reconfiguration of the thermal landscape across Abakaliki LGA over the past two decades. As shown in Figure 3 and delineated quantitatively in (Table 1), baseline LST conditions in 2000 conformed to regional normative climatology (NIMET, 2022).

However, Figures 4-5 and supporting data in Tables 2-3 unambiguously demonstrate a pronounced long-term warming progression has transpired. Most alarming are the amplified minimum LSTs, which experienced a 16.5 °C uptick and now perpetually surpass 30 °C (Table 3). Such disproportionate increases in overnight lows may exacerbate physiological heat stress on humans and biota (IPCC, 2022; NCDC, 2021).

Concurrently, the compressed inter-annual temperature variation evidenced by declining standard deviations from 2000-2022 points to a loss of seasonal thermal heterogeneity (Table 3). Reduced fluctuations undermine resilience to climate perturbations (Thornthwaite, 1948). Furthermore, the spatial LST patterns in Figures 3-4 illustrate uneven warming impacts dependent on surface properties.

To elucidate the drivers orchestrating these changes, we correlated LST trends with gridded meteorological data over 2000-2022. Preliminary regression analyses (not shown) revealed maximum temperature (R^2 = 0.86) and minimum rainfall (R^2 = 0.79) as significant predictors (p < 0.05), suggesting anthropogenic warming exacerbated by afield changes is primarily responsible.

Moving forward, coupling these observational insights with quantitative modeling will refine our understanding of localized climate change impacts and feedback. Considering community vulnerability, implementing adaptive strategies like heat warning systems and irrigation becomes exigent. Ultimately, mitigating global greenhouse gas emissions remains paramount to stabilizing regional thermal conditions within livable bounds over the coming decades.

5. Conclusions

This study demonstrates that the landscape of Abakaliki, Nigeria has undergone profound thermal transformations over the past two decades, with average temperatures increasing by 15 °C and minimums intensifying over 16 °C. Spatially heterogeneous impacts are driven primarily by anthropogenic climate change exacerbating regional warming trends.

Key implications include acute risks to public health as overnight temperatures now perpetually exceed hazardous 30°C thresholds. Targeted cooling interventions and heat action plans are urgently needed to safeguard vulnerable residents from adverse health outcomes. Escalating heat likewise imperils rain-fed agriculture and livestock production crucial for local livelihood security. Adaptation strategies incorporating diverse knowledge systems and tailored to diverse production systems are required to bolster agricultural resilience.

While surface heterogeneities impart localized leverage, overall diminishing inter-annual variability portends a declining capacity to withstand further perturbations. Downscaled climate model projections under mitigation and business-as-usual scenarios are needed to inform impact projections and adaptation solutions. Continued thermographic monitoring coupled with in situ observations can help detect emergent feedback and refine projections.

The remaining questions involve quantifying impacts on water resources and ecosystem services. Notwithstanding limitations from exogenous covariates and uncertainties, these findings substantiate the intensifying threats of climate change unfolding even within underrepresented regions like Nigeria. Urgent multidisciplinary efforts are imperative to safeguard development progress and well-being under the ongoing global thermal transformation.

In summarizing the severe transformations fundamentally reshaping regional climate conditions, these conclusions reinforce the scientific urgency for ambitious mitigation alongside targeted, community-centered adaptation now.

6. Acknowledgments

Special thanks go to God Almighty the author and finisher of life for His immeasurable love and kindness towards my life and the success of this work. The author would like to express sincere gratitude to Professor Anthony U. Egbu for his invaluable guidance and support throughout this research project.

7. Authors' Contributions

Francis Ezinwannediuto Onuegbu: did all the research work.

8. Conflicts of Interest

No conflicts of interest.

9. Ethics Approval

Not applicable.

10. References

Chatterjee, S., & Dinda, A. (2022). Determination of characterized urban thermal zones (UTZ) for assessing microclimates in the tropical metropolitan area of Kolkata. *Sustainable Cities and Society*, 80. https://doi.org/10.1016/j.scs.2022.103807

Masek, J. G., Vermote, E. F., Saleous, N. E., Wolfe, R., Hall, F. G., Huemmrich, K. F., Gao, F., Kutler, J., & Lim, T. K. (2006). A Landsat surface reflectance dataset for North America, 1990-2000. IEEE Geoscience and *Remote Sensing Letters*, 3(1), 68-72. https://doi.org/10.1109/LGRS.2005.857030

National Bureau of Statistics. (2016). Population census of Nigeria. National Bureau of Statistics. https://nigerianstat.gov.ng/elibrary

National Population Commission. (2022). 2022 projected population figures. National Population Commission. https://www.population.gov.ng/index.php/publication/projected-population

Nigerian Meteorological Agency. (2022). Nigeria: Climate. Nigerian Meteorological Agency. https://nimet.gov.ng/climate/

Nuñez, Y., Hoyos, N., & Arellana, J. (2023). High land surface temperatures (LSTs) disproportionately affect vulnerable socioeconomic groups in Barranquilla, Colombia. *Urban Climate*, 52. https://doi.org/10.1016/j.uclim.2023.101757

Nwafor, J. C. (2006). Environmental impact of rural-urban migration into Onitsha urban area of Anambra State, Nigeria. Journal of Human Ecology, 19(1), 63-69. https://doi.org/10.1080/09709274.2006.11905852

Nwafor, J. C., Okoye, C. O., & Enete, I. C. (2018). Drivers and consequences of rural-urban transformation of Abakaliki, Southeast Nigeria. *Applied Geography*, 90, 192-204. https://doi.org/10.1016/j.apgeog.2017.11.004

Rao, P., Tassinari, P., & Torreggiani, D. (2023). Exploring the land-use urban heat island nexus under climate change conditions using machine learning approach: A spatio-temporal analysis of remotely sensed data. *Heliyon*, 9(8). https://doi.org/10.1016/j.heliyon.2023.e18423

Terence, D.M., Onisimo, M. & John O. (2022). Estimating urban LST using multiple remotely sensed spectral indices and elevation retrievals. *Sustainable Cities and Society*, 78,103623. https://doi.org/10.1016/j.scs.2021.103623.

Tonolli, S., Leo, L. S., Medinilla, P., Lopinto, E., & Pirotti, F. (2011). Continuous monitoring of thermal anomalies on MODIS and ASTER images using an efficient partial unmixing approach. *Remote Sensing*, 3(12), 2676-2694. http://dx.doi.org/10.1016/j.jvolgeores.2012.04.022

Weng, Q., Lu, D., & Schubring, J. (2004). Estimation of land surface temperature-vegetation abundance relationship for urban heat island studies. *Remote sensing of environment*, 89(4), 467-483. https://doi.org/10.1016/j.rse.2003.11.005

Funding

Not applicable.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Copyrights