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Quantification of the Influence of Cloud on Diurnal Urban Heat Island Across Climatic Belts in Nigeria

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ABSTRACT

The study quantified the influence of clouds on diurnal (day and night) urban heat islands across climatic belts in Nigeria from 2003 to 2022. Remote sensing techniques were utilized to collect data such as Land Surface Temperature, GPS ground truth points, MODIS & Landsat images, and cloud cover data from CRU-TS spanning 20 years. The study covered urban and rural areas in Nigeria, with a sample size of 160 points distributed across eight cities. Statistical analysis, performed through SPSS, showed significant impacts of cloud cover variations on UHI dynamics ($F = 7.837$, $p = 0.012$). Diurnal UHI exhibited a significant difference ($H = 59.15$, $P=.001$). Urban expansion was identified as exacerbating UHI effects, emphasizing the urgency of sustainable urban planning strategies. The study reiterated the necessity of tailored mitigation plans, considering diverse UHI patterns across cities and climatic zones. Therefore, the study advocates evidence-based urban planning for UHI mitigation and climate resilience. Recommendations include prioritizing green infrastructure and integrating cloud cover and wind speed variations into urban planning strategies.

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Introduction

Urbanization in Nigeria has spurred the emergence of the urban heat island (UHI) effect, characterized by heightened temperatures in urban areas compared to their rural surroundings [1]. This phenomenon presents multifaceted challenges, including impacts on human health, energy consumption, and environmental sustainability [2]. Despite the recognition of various drivers of UHI intensity, such as land cover changes and anthropogenic heat emissions, the specific influence of cloud cover on diurnal variations of UHI across different climatic belts in Nigeria remains insufficiently understood. This knowledge gap poses a significant barrier to the development of targeted mitigation strategies aimed at alleviating the adverse effects of UHI on urban residents and ecosystems [3]. Globally, cloud cover has been identified as a critical modulator of surface temperatures in urban environments, with its role in attenuating or amplifying UHI effects depending on factors such as cloud type, coverage, and temporal variation [4]. Nigeria's diverse climatic zones, ranging from tropical rainforests in the south to arid conditions in the north, present unique atmospheric dynamics and cloud cover patterns that can influence the intensity and temporal variation of UHI [5]. Integrating remote sensing techniques, Geographic Information Systems (GIS) analysis, and climatic data offers promising avenues for quantifying the relationship between cloud cover and diurnal UHI variations across climatic belts in Nigeria [6]. Understanding these complex interactions is crucial for informing evidence-based urban planning decisions, climate adaptation strategies, and public health interventions aimed at mitigating the adverse effects of UHI in Nigeria and other tropical regions facing similar challenges associated with rapid urbanization and climate change.

Materials and Methods

Study Area

The study focuses on Nigeria, a country located in West Africa, bordered by Benin to the west, Niger to the north, Chad to the northeast, and Cameroon to the east. To the south, it is bordered by the Gulf of Guinea, providing access to the Atlantic Ocean. Nigeria's geographic coordinates range from approximately 4° to 14° North latitude and 3° to 15° East longitude, spanning a total area of around 923,768 square kilometers [7]. The country encompasses diverse climatic zones, including tropical rainforests in the south, savannas and woodlands in the central regions, and arid and semi-arid conditions in the north, influenced by the West African monsoon system and the intertropical convergence zone (ITCZ) [8]. This geographic and climatic diversity makes Nigeria an ideal location for studying the influence of cloud cover on diurnal variations of the urban heat island phenomenon across different climatic belts. The study focuses on eight (8) major urban areas across different climatic belts i.e. Tropical Wet Climate (Lagos & Port Harcourt), Tropical Savanna (Abuja & Enugu), Hot Semi-Arid (Kano, Kastina & Maiduguri) and Montane (Jos) in Nigeria.

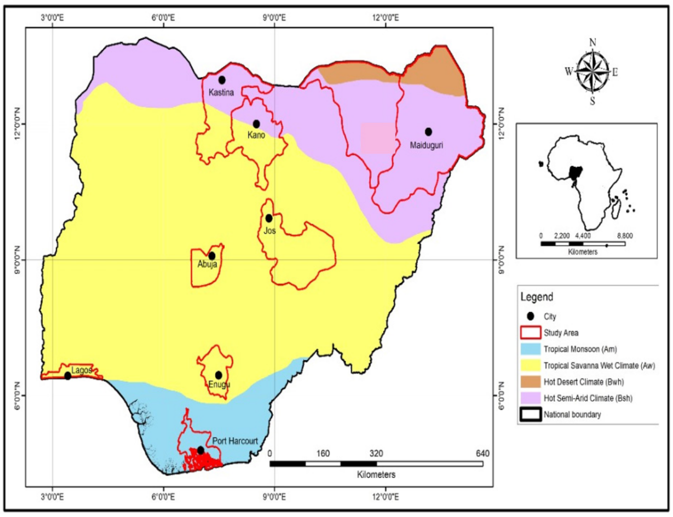

Figure 1: Study area showing the Four Climatic Belts of Nigeria.

Source: Dept of Geography Cartography Laboratory, Uniport. 2023

Data Collection and Analysis
Data on temperature, humidity, wind speed, and cloud cover at regular intervals throughout the day and night were collected from the Nigerian Meteorological Agency (NiMet) stations strategically located to cover different climatic belts. The data covered a period of 20 years (2003 to 2022) across climatic belts in Nigeria. Time series Cloud Cover (2003 to 2022) from the archives of the Climatic Research Unit (CRU-TS) high resolution gridded time series datasets was obtained and used. Secondary data such as MODIS Land Surface Temperature and Emissivity (MODIS 11) was made use of. This was used to validate the temperature of other areas within the selected cities. The MODIS 11 was also used because of the anomalies of the Landsat imageries and the difference in determining land surface temperature is a maximum of ± 2 °C [9]. Some point data were then used to capture the actual temperature value using the zonal statistics tool in the ArcGIS platform. To collect data on Land Surface Temperature, Moderate Resolution Imaging Spectro-radiometer (MODIS) imageries for 20 epochs (2003 to 2022) from the archives of NASA (https://ladsweb.modaps.eosdis.nasa.gov/: was accessed on the 15th of May 2023) from Level-1 and Atmosphere Archive & Distribution System Distributed Active Archive Center (LAADS DAAC) backup source and were used as secondary data to generate land surface temperature values that enabled for the determination of Urban Heat Island (UHI) fluxes in the selected cities and their suburbs across Nigeria. Also, to analyze the cloud cover data, the study employed ArcGIS Software as a basic analysis tool. The acquired Climatic Research Unit (CRU-TS) high resolution gridded time series datasets were acquired in NetCDF format. The cloud cover NetCDF format data were extracted to raster layers using the Multidimensional tool in the ArcToolbox. These raster layers were further analysed in the GIS environment to calculate for monthly averages in cloud cover within the study period for the study area. The key interpolation method adopted was the Inverse Distance Weighting (IDW) algorithm under Spatial Analyst Tool in the ArcToolbox to generate cloud cover information for the study area. The advantage of the IDW method is this: it is easy to define and therefore easy to understand the results because an interpolating point is most influenced by a nearby points and less by the more distant points "the principle of spatial auto-correlation or Tobler's First Law of Geography" (Burrough & McDonnell, 1998).

Use statistical methods such as regression analysis to identify correlations between cloud cover, urban heat island intensity, and other meteorological variables. Conduct a time-series analysis to examine temporal trends in cloud cover and urban heat island effects throughout the day and night.

Results and Discussion
The influence of clouds on the UHI during the Dry season across the climatic belts in Nigeria in January between 2003 and 2022. Secondary data such as MODIS Cloud cover (MOD11) were used. This covers the study period January between 2003 and 2022.

Table 1: Spatial Analysis of cloud cover reading during Dry season for each city from 2003 to 2022 in percentage cloud coverage

YEAR	PH	LAGOS	ENUGU	ABUJA	JOS	KANO	KATSINA	MAIDUGUI
	Low - High	Low - High	Low - High	Low - High	Low - High	Low - High	Low - High	Low - High
2003	75.1 -78.1	61.0 - 61.8	60.1 - 62.7	45.4 - 47.1	42.2 - 43.3	38.3 - 42.3	19.9 - 24.3	27.8 - 31.7
2004	75.9 - 78.6	66.1 - 66.9	60.2 - 62.9	46.1 - 47.5	42.9 - 44.2	39.8 - 44.0	21.6 - 25.0	27.3 - 31.2
2005	74.1 - 76.9	64.0 - 65.1	59.4 - 61.6	46.9 - 47.5	43.9 - 45.1	41.6 - 44.4	25.4 - 25.7	34.9 - 38.8
2006	74.6 - 77.4	64.2 -65.4	59.3 - 61.6	44.1 - 45.6	41.1 - 41.7	33.8 - 36.3	15.5 - 15.8	23.3 - 27.4
2007	75.3 - 78.1	64.8 - 66.1	59.4 - 61.8	46.6 - 47.2	45.4 - 47.3	45.3 - 48.0	28.0 - 28.3	29.6 - 33.3
2008	75.9 - 78.5	73.6 - 74.8	59.6 - 62.0	48.1 -48.6	45.5 - 47.3	45.4 - 48.4	29.3 - 29.6	30.9 - 34.6
2009	75.9 - 78.5	70.4 - 71.6	59.6 - 61.9	47.7 - 48.2	45.8 - 47.7	45.4 - 47.6	25.8 - 26.4	32.4 - 36.0
2010	73.8 - 76.9	56.6 - 57.8	59.1 - 61.4	44.5 - 45.8	41.9 - 42.7	35.8 - 38.3	17.6 - 17.9	25.6 - 29.9
2011	77.8 - 79.0	77.9 - 78.4	68.8 - 70.8	56.6 - 57.7	45.9 - 48.9	50.9 - 52.1	38.9 - 40.2	44.1 - 45.1
2012	76.8 - 78.6	62.3 - 62.4	63.4 - 66.2	48.2 - 49.6	44.2 - 46.8	48.9 - 50.4	34.4 - 34.8	38.9 - 40.3
2013	76.8 - 78.6	60.1 - 60.3	63.9 - 66.2	48.1 - 49.5	43.9 - 46.5	49.1 - 50.8	35.3 - 35.8	38.7 - 40.2
2014	76.5 - 78.2	61.5 - 61.6	63.3 - 66.1	48.8 - 49.9	45.2 - 47.5	51.7 - 53.6	38.9 - 39.6	37.9 - 39.4
2015	76.4 - 78.0	61.4 - 61.5	63.3 - 66.0	48.1 - 49.7	42.5 - 45.7	44.6 - 46.3	31.7 - 32.6	41.6 - 42.6
2016	76.8 - 78.7	67.1 - 67.3	63.4 - 66.3	50.0 - 50.9	49.2 - 50.5	63.4 - 64.8	48.4 - 48.5	51.8 - 53.0
2017	77.1 -79.1	72.8 - 73.1	63.6 - 66.5	49.5 - 50.4	46.5 - 48.3	56.1 - 57.9	43.2 - 43.7	44.1 - 45.4
2018	76.8 - 78.7	68.5 - 68.8	63.5 - 66.3	51.2 - 51.8	50.4 - 52.0	65.4 - 67.8	50.6 - 51.2	43.9 - 44.8
2019	77.3 - 79.5	71.5 - 71.8	63.6 - 66.5	48.2 - 49.6	45.8 - 47.5	51.5 - 52.7	35.8 - 36.3	41.4 - 42.9
2020	77.4 - 79.6	72.1 - 72.5	63.8 - 66.7	48.2 - 49.7	43.3 - 46.1	46.4 - 47.7	30.7 - 30.8	38.7 - 40.1
2021	77.0 - 78.5	70.5 - 71.6	64.9 - 66.8	53.0 - 54.1	45.1 - 48.9	43.7 - 45.6	23.2 - 24.3	38.0 - 41.2
2022	76.3 - 78.3	56.6 - 60.7	65.5 - 67.3	54.4 - 55.2	46.4 - 47.8	45.6 - 47.5	25.7 - 26.7	38.5 - 41.7

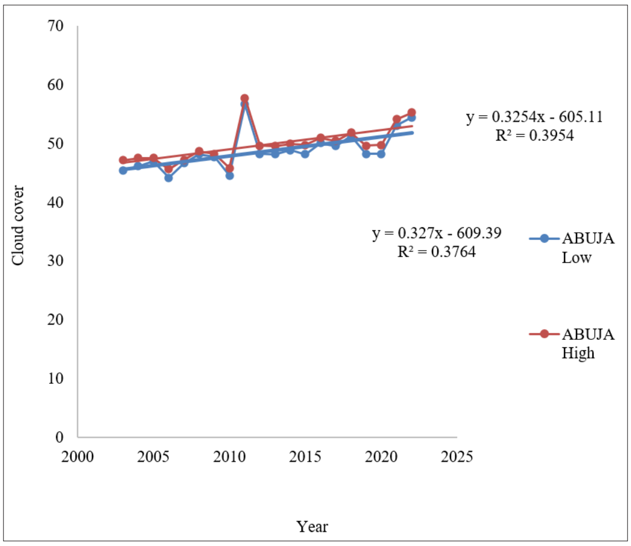

Figure 2: Average Dry Season cloud cover in Abuja in January between 2003 and 2022

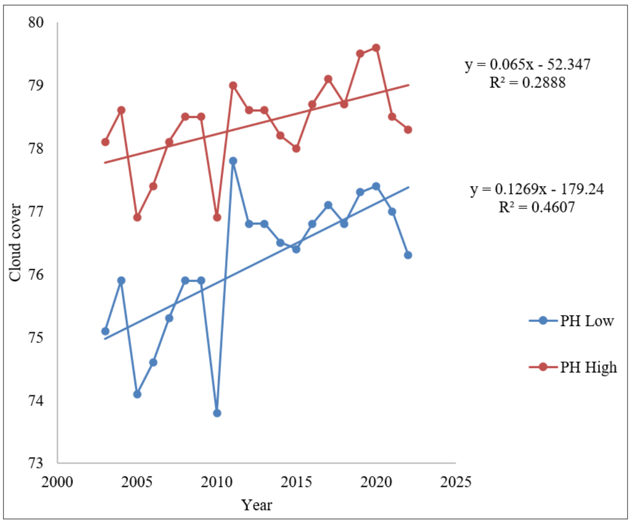

Figure 3: Average Dry Season cloud cover in Port Harcourt in January between 2003 and 2022

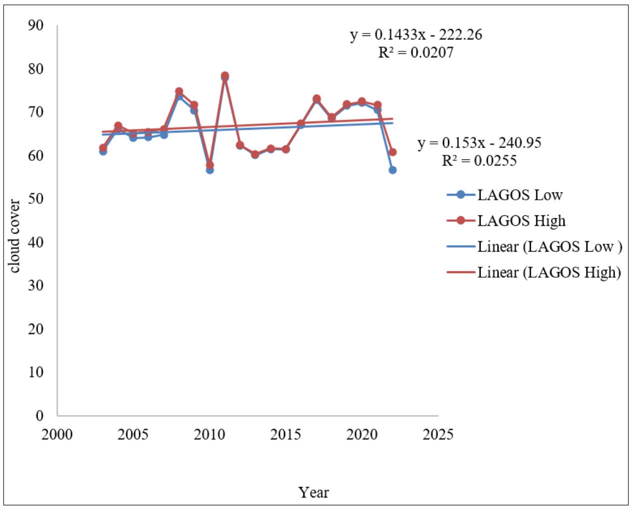

Figure 4: Average Dry Season cloud cover in Lagos in January between 2003 and 2022

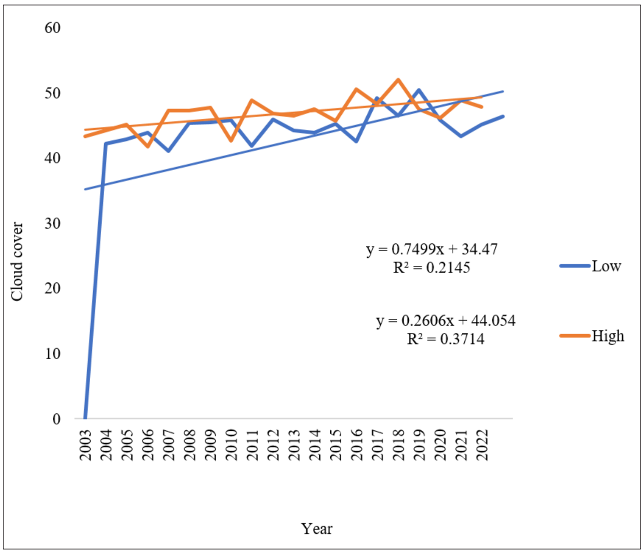

Figure 5: Average Dry Season cloud cover in Jos in January between 2003 and 2022

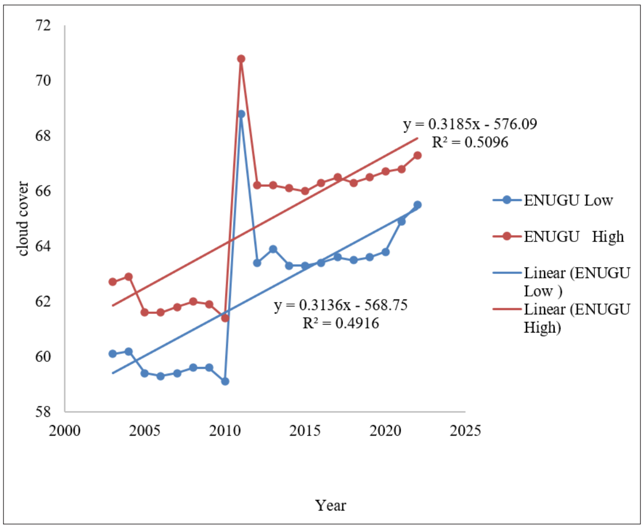

Figure 6: Average Dry Season cloud cover in Enugu in January between 2003 and 2022

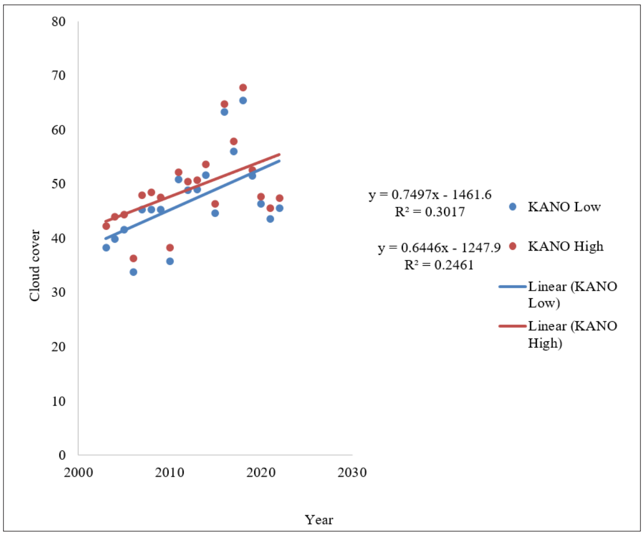

Figure 7: Average Dry Season cloud cover in Kano in January between 2003 and 2022

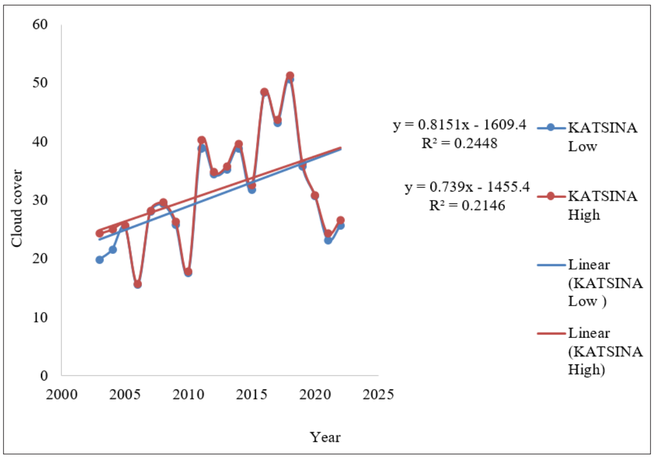

Figure 8: Average Dry Season cloud cover in Katsina in January between 2003 and 2022

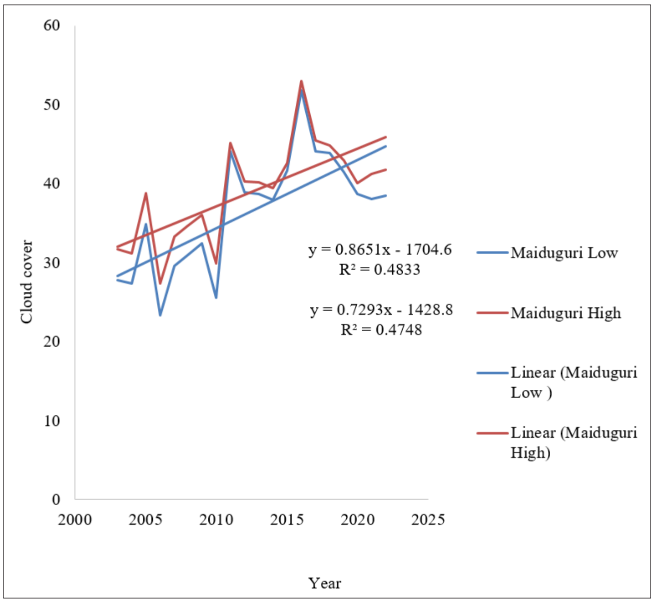

Figure 9: Average Dry Season cloud cover in Maiduguri in January between 2003 and 2022

The Influence of Clouds on the UHI During Wet Season Across the Climatic Belts in Nigeria in July between 2003 and 2022.

Table 2: Spatial distribution of Cloud cover Reading During wet Season for each city in Percentage Cloud Coverage from 2003 to 2022

YEAR	PH	LAGOS	ENUGU	ABUJA	JOS	KANO	KATSINA	MAIDUGUR
	Low - High	Low - High	Low - High	Low - High	Low - High	Low - High	Low - High	Low - High
2003	95.7 - 95.9	85.2 - 86.2	90.9 - 92.1	83.7 - 84.9	78.8 - 80.9	58.9 - 62.6	42.4 - 42.5	60.4 - 64.7
2004	95.8 - 96.1	87.7 - 88.8	90.9 - 92.1	83.7 - 84.8	78.1 - 80.5	57.5 - 61.3	41.0 - 41.1	60.3 - 64.6
2005	96.1 - 96.5	94.8 - 95.9	90.9 - 92.1	83.8 - 84.9	78.9 - 80.9	58.9 - 62.6	42.5 - 42.5	60.3 - 64.7
2006	96.0 - 96.4	89.7 - 90.7	90.9 - 92.1	83.7 - 84.9	78.8 - 80.9	58.9 - 62.6	42.4 - 42.5	60.4 - 64.7
2007	96.0 - 96.3	94.5 - 95.5	90.9 - 92.1	83.9 - 85.0	78.6 - 80.8	58.6 - 62.3	42.2 - 42.2	60.4 - 64.7
2008	96.1 - 96.5	94.1 - 95.0	90.9 - 92.1	84.4 - 85.2	80.3 - 82.1	62.3 - 66.1	45.9 - 46.0	60.6 - 65.0
2009	96.1 - 96.5	90.7 - 91.7	90.9 - 92.1	83.0 - 84.4	75.2 - 78.6	51.4 - 55.3	34.7 - 34.9	59.9 - 64.0
2010	95.9 - 96.2	88.6 - 89.7	90.9 - 92.1	84.0 - 85.0	78.8 - 80.9	58.9 - 62.6	42.5 - 42.6	60.4 - 64.5
2011	95.7 - 96.2	93.0 - 94.4	94.1 - 95.3	88.5 - 89.1	87.8 - 88.6	72.7 - 74.6	59.5 - 60.3	76.9 - 78.6
2012	95.5 - 96.5	94.5 - 95.4	93.5 - 94.7	86.2 - 86.8	82.5 - 83.6	67.3 - 69.5	51.8 - 52.3	68.1 - 70.4
2013	95.4 - 96.3	93.1 - 94.1	93.4 - 94.6	85.5 - 86.3	81.8 - 82.8	62.6 - 64.9	46.3 - 46.5	67.0 - 69.8
2014	95.8 - 96.9	99.9 - 100.0	93.6 - 94.9	85.7 - 86.5	80.8 - 82.7	62.1 - 64.5	45.7 - 45.9	66.9 - 69.7
2015	94.5 - 95.3	82.5 - 83.6	93.0 - 94.2	85.2 - 86.0	82.8 - 83.7	68.2 - 70.3	52.2 - 52.3	68.3 - 70.4
2016	94.9 - 95.7	89.5 - 90.5	93.2 - 94.4	85.4 - 86.1	83.5 - 84.1	70.5 - 72.4	54.3 - 54.5	68.8 - 70.8
2017	95.7 - 96.7	93.9 - 94.9	93.4 - 94.7	85.3 - 86.2	81.4 - 82.9	63.7 - 66.1	47.4 - 47.4	67.3 - 69.9
2018	95.2 - 96.0	90.7 - 91.7	93.3 - 94.5	85.5 - 86.3	80.7 - 82.9	61.5 - 63.9	45.3 - 45.7	66.8 - 69.6
2019	93.5 - 94.6	76.8 - 78.0	92.7 -93.8	85.4 - 86.2	82.1 - 83.3	66.0 - 68.2	49.9 - 50.0	67.8 - 70.1
2020	95.4 - 96.4	96.8 - 97.7	93.5 - 94.7	85.9 - 86.6	81.7 - 83.2	61.8 - 67.1	48.8 - 49.0	67.5 - 70.0
2021	95.7 - 95.9	86.9 - 89.1	91.5 -92.6	83.5 - 84.8	79.9 - 82.0	60.3 - 63.2	41.1 - 42.1	60.1 - 64.8
2022	96.3 - 96.3	93.2 - 95.3	91.6 - 92.9	84.5 - 85.4	82.1 - 83.5	64.8 - 67.6	45.7 - 46.7	61.3 - 65.8

Results of the trend analysis of cloud cover for the wet season is assessed with the lowest values in the legend representing areas with low cloud cover visibility while high values indicate high atmospheric cloud cover visibility. From the analysis, the marked variation in cloud cover exists over time across the selected cities. The variability of cloud cover during the wet season revealed that, Katsina and Kano had the highest variation rate of 0.360 and 0.307, while Maiduguri recorded 0.242, Abuja 0.063 with Jos and Enugu witnessing almost similar cloud cover values of 0.154 and 0.120. In the same vein, the cloud cover of Abuja, Enugu, and Jos were similar while Lagos and Port Harcourt witnessed the least cloud cover variation rate ranging from -0.019 and -0.022 during the wet season. From the analysis, negative trend in cloud variation was observed only in the Tropical Wet climate while positive variation was exhibited in the other climatic belts.

Hypothesis: There is no significant relationship in the influence of Cloud Cover on UHI from the years 2003 and 2022.

Table 3: Analysis of Variance of Regression on the Influence of Cloud Cover on UHI from the Years 2003 and 2022.

Model		Sum of Squares	Df	Mean Square	F	Sig.
	Regression	7.583	1	7.583	7.837	.012
	Residual	17.417	18	.968		
	Total	25.000	19			

a. Dependent variable: UHI from the year 2003 and 2022.
b. Predictor: (Constant): Influence of Cloud

Table 3 shows that the F-value of 7.837 is significant at .012. This indicated that the UHI from 2003 to 2022 was significantly related to the influence of cloud. Therefore, the null hypothesis of no significant linear relationship between the influence of cloud on UHI from the years 2003 and 2022 was rejected.

Table 4: Model Summary on the Influence of Cloud on UHI from the years 2003 and 2022

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
	.551	.303	.265	.98366

Predictor: (Constant), Cloud

The coefficient of determination (R2) is .303. This indicates that 9.18% of the variance in the UHI from 2003 to 2022 is caused by variations in the predictor variable (influence of Cloud). Therefore, 9.18% of the variance in the UHI from the year 2003 to 2022 is predicted by the influence of cloud.

Table 3: t-values of UHI from the year 2003 to 2022 and the Influence of Cloud

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-14.218	5.976		2.379	.029
Cloud	.249	.089	.551	2.800	.012

(** Sig. at $P < 0.05$), dependent variable: UHI 2003 to 2022

To determine if the predictor variable (influence of cloud) was significantly related to or predicted the UHI from 2003 to 2022, the t-value was presented in Table 3. The t-value for the influence of cloud was 2.379, $P < 0.29$). The influence of cloud had a significant relationship ($P < 0.029$) with and predicted the UHI from the year 2003 to 2022.

Discussion of Findings

This research examined the influence of clouds on the Urban Heat Island (UHI) effect during the dry and wet seasons across various climatic belts in Nigeria from January 2003 to January 2022, utilizing MODIS Cloud cover data (MOD11). The analysis revealed significant variations and trends in cloud cover over time, highlighting differences across the selected cities.

During the dry season, the trend analysis indicated an overall increase in cloud cover across all cities, with the most substantial increases observed in Katsina (0.739) and Maiduguri (0.729), and the smallest increase in Port Harcourt (0.065). This upward trend suggests a potential mitigating effect on the UHI, as increased cloud cover can reduce surface temperatures by limiting solar radiation. However, the extent of this mitigation varies regionally, influenced by local climatic conditions and urban characteristics.

In contrast, the wet season analysis showed mixed trends. Katsina and Kano exhibited the highest increases in cloud cover (0.360 and 0.307, respectively), while Lagos and Port Harcourt showed slight negative trends (-0.019 and -0.022). The negative trends observed in these coastal cities might be linked to their tropical wet climate, which typically experiences consistent high humidity and rainfall, reducing the variability of cloud cover. The differences in cloud cover trends between seasons underscore the complexity of atmospheric interactions and their impact on UHI.

Comparing these findings with existing literature, the results align with studies that have shown cloud cover plays a significant role in modulating urban temperatures. For instance, increased cloud cover is generally associated with lower daytime temperatures and reduced UHI intensity due to decreased solar insolation (Mao et al., 2019). But clouds can also increase nighttime UHI because they retain longwave radiation that is released into space, underscoring the double function of clouds in controlling urban climate (Sobstyl et al., 2018).

The implications of these findings are substantial for urban planning and climate adaptation strategies. The observed increase in cloud cover during the dry season across most cities suggests a potential natural buffer against extreme heat events. However, urban areas must also consider the potential for increased nocturnal warming due to cloud cover. Understanding these dynamics can inform the development of urban green spaces and reflective surfaces to further mitigate UHI effects.

The findings emphasize the need for tailored urban climate strategies that consider both seasonal and regional variations in cloud cover to effectively mitigate UHI impacts and enhance urban resilience to climate change [10-21].

Conclusion

In conclusion, this study underscores the significant influence of cloud cover on the Urban Heat Island (UHI) effect across various climatic belts in Nigeria. The analysis revealed notable trends in cloud cover during both the dry and wet seasons, with implications for urban temperature regulation. While increased cloud cover during the dry season may offer a natural buffer against extreme heat events, the variability of cloud cover across seasons and regions necessitates tailored climate adaptation strategies.

Based on these findings, the following recommendations are proposed. First, implement integrated monitoring systems combining satellite-derived data with ground-based observations to enhance the accuracy and resolution of cloud cover analysis. Second, encourage the development of urban green spaces and reflective surfaces to mitigate the Urban Heat Island effect and counteract potential nocturnal warming associated with increased cloud cover. Third, incorporate climate-resilient urban planning strategies that consider both seasonal and regional variations in cloud cover to effectively mitigate UHI impacts and enhance urban resilience to climate change. Finally, conduct long-term research to assess the evolving dynamics of cloud cover and its impact on the Urban Heat Island effect, considering broader climatic trends and urbanization patterns. By implementing these recommendations, policymakers, urban planners, and stakeholders can work towards creating more sustainable and climate-resilient cities in Nigeria and beyond.

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