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Analyzing Temperature Trends and Projecting Future Climate Scenarios for Port Harcourt Using CMIP6 Models

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Abstract

This study analyzes historical temperature trends (minimum and maximum) in Port Harcourt from 1993 to 2023 and projects future scenarios using Coupled Model Intercomparison Project Phase 6 (CMIP6) models. Monthly temperature data from the Nigerian Meteorological Agency (NiMET) were assessed using linear regression and the Mann-Kendall trend test to identify temporal trends. Boxplots were employed to visualize monthly temperature variations, while bar charts were used to highlight decadal changes in mean surface temperature. Two Shared Socioeconomic Pathway (SSP) scenarios—SSP2-4.5 (intermediate emissions) and SSP5-8.5 (high emissions)—were applied to project temperature changes through the year 2100, incorporating uncertainty bands (±1°C). Extreme heat events, defined as daily temperatures exceeding 34.5°C, were also analyzed for frequency across distinct decades. The results reveal a baseline mean temperature of 31.58°C for 1993–2023 with a noticeable warming trend. Decadal temperature shifts include a slight decrease of -0.07°C from the 1990s to 2000s, followed by increases of +0.36°C (2000s–2010s) and +0.53°C (2010s–2020s). Linear regression analysis indicates a steady rise of 0.025°C per year, supported by the Mann-Kendall test, confirming significant warming. Future projections under SSP2-4.5 estimate an increase in mean temperature to approximately 33.7°C by 2100. Under the more extreme SSP5-8.5 scenario, temperatures may rise to 35.1°C. Extreme heat events (>34.5°C) are projected to occur on up to 110 days per year under SSP5-8.5 by the century's end. February remains the hottest month (mean 34.23°C), while July and August are the coolest (mean ~29.0°C). These findings highlight the urgent need for investments in climate-resilient infrastructure, including energy-efficient buildings and heat-reducing urban designs, to protect public health and enhance adaptive capacity in Port Harcourt.

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Introduction

Climate change, predominantly instigated by anthropogenic activities such as the combustion of fossil fuels and deforestation, has precipitated a noteworthy escalation in global temperatures. The Intergovernmental Panel on Climate Change (IPCC) indicates that since the latter part of the 19th century, global temperatures have elevated by approximately 1.1°C, a phenomenon intricately associated with heightened concentrations of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (IPCC, 2021). These gases facilitate the entrapment of heat within the Earth's atmosphere, engendering climatic transformations characterized by an increase in the frequency of heat waves, modifications in precipitation patterns, and the phenomenon of rising sea levels. Studies by Rahmstorf *et al.* (2017) and Hansen *et al.* (2019) elucidate that the velocity of global temperature augmentation is accelerating, posing significant ramifications for ecosystems, human health, and the global economy. The trend has manifested particularly markedly since the mid-20th century, with the preceding four decades exhibiting temperatures that surpassed those of any previous decade since 1850 (IPCC, 2021). In geographical contexts such as Nigeria, particularly in coastal urban areas like Port Harcourt, susceptibility to climate change is exacerbated by geographic and socioeconomic determinants. Coastal urban centers are at the vanguard of climate variability and encounter distinct challenges, including rising sea levels, coastal erosion, and temperatures (Zhuge *et al.*, 2024). The southern coastal regions of Nigeria, including Port Harcourt, are especially vulnerable to extreme meteorological phenomena such as flooding and storms. Empirical studies have indicated that Nigeria has undergone a temperature increase in recent decades, with more pronounced warming trends in urban centers like Lagos, attributable to urbanization and their proximity to maritime environments (Onyedikachi *et al.*, 2024). Elevated temperatures amplify the risks associated with heat stress, infrastructural damage, and challenges to public health (Ebi *et al.*, 2021). Hence,

April, Volume 11, Number 2, Pages 79 - 87 http://www.ijbst.fuotuoke.edu.ng /80
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examining temperature trends in Port Harcourt is imperative, given that its expanding population and industrial undertakings render it particularly vulnerable to risks induced by climate change.

The analysis of temperature variations in Port Harcourt over the preceding three decades is vital for several reasons. Longitudinal climate data can elucidate trends that may be overlooked in more abbreviated studies, thereby furnishing valuable insights into the progression of warming. For instance, research underscores that the escalating temperatures in Port Harcourt are exacerbating health issues related to heat, disrupting agricultural practices, and amplifying energy demands for cooling mechanisms (Nwaerema *et al.,* 2019). Furthermore, increased temperatures are correlated with the frequency of flooding occurrences, particularly within coastal areas. Comprehending these temperature dynamics is vital for informing climate adaptation initiatives in Port Harcourt, as projections indicate that global temperatures are poised to perpetuate their ascent (Echendu, 2025; Okoro *et al.,* 2022). Insights can assist policymakers in formulating strategies aimed at mitigating the consequences of climate change and protecting the city's infrastructure and populace.

Additionally, climate projection models constitute essential instruments for efficacious planning in anticipation of prospective climate risks. These models furnish insights into future climatic patterns, aiding policymakers and communities in their preparations for potential hazards. They can predict changes in temperature, precipitation, and extreme weather events, which are critical for devising long-term adaptation strategies in vulnerable locales such as Port Harcourt (Danladi *et al.*, 2017). Without these projections, formulating effective strategies to mitigate the repercussions of climate change on these communities would prove to be arduous. The increase in global temperatures is driven by human activities, especially the release of greenhouse gases. Empirical research suggests that the global temperature has ascended by approximately 1.2°C since the latter part of the 19th century, resulting in ramifications such as altered climatic patterns, the thawing of polar ice, and elevated sea levels. The mitigation of climate change will necessitate substantial reductions in emissions stemming from fossil fuel combustion, deforestation, and industrial activities. The Sixth Assessment Report of the IPCC accentuates the urgent necessity to confront global warming, highlighting the irrefutable role of human activities in its swift intensification. If greenhouse gas emissions are not reduced, constraining global warming to 1.5°C above pre-industrial levels will be nearly unattainable (IPCC, 2021). Extreme thermal events, including heatwaves, are becoming increasingly prevalent and severe, particularly in regions such as Africa, where phenomena like heatwaves, droughts, and floods are amplifying. West Africa, notably Nigeria, has undergone significant warming trends, which present risks to agriculture, public health, and freshwater resources (Ayanlade *et al.,* 2022). These trends underscore the necessity for integrated climate models to forecast future thermal scenarios and inform intervention strategies.

Coastal metropolises such as Port Harcourt are particularly susceptible to the ramifications of climate change. In recent decades, urban centers in Nigeria's Niger Delta, including Port Harcourt, have witnessed considerable increases in temperature attributable to urbanization, deforestation, and global climatic alterations. Research, including findings from the Nigerian Meteorological Agency (NiMet), reveals a general warming trajectory in Port Harcourt, which aligns with the temperature trends. The dry season experiences more intense warming compared to the wet season. Nonetheless, investigations concerning Port Harcourt's temperature trends rely on short-term datasets, frequently encompassing 10 to 20 years. There exists a substantial deficiency in long-term studies that would yield a more comprehensive understanding of the city's climatic dynamics and vulnerability to global warming. In climate modeling, instruments such as the Coupled Model Intercomparison Project Phase 6 (CMIP6) have become indispensable in projecting prospective climatic scenarios. CMIP6 enhances previous iterations of climate modeling by integrating advancements in model resolution, complexity, and data assimilation methodologies. These enhancements facilitate a more nuanced comprehension of climatic variability and regional ramifications. CMIP6 includes models from over 100 global institutions, addressing climatic processes. These models help scientists and policymakers understand how greenhouse gases, aerosols, and land use affect past and future changes in the climate system. In tropical regions such as West Africa, CMIP6 models are essential for investigating extreme weather phenomena, including heatwaves, temperature fluctuations, and intense rainfall, which are becoming increasingly frequent due to climate change. CMIP6 models have advanced in terms of resolution and parameterization of critical processes, but uncertainties persist, particularly about temperature, rainfall variability, cloud formation, and feedback mechanisms that simulate local climate. While CMIP6 models furnish a robust framework for climate projection, limitations remain.

International Journal of Basic Science and Technology
April, Volume 11, Number 2, Pages 79 - 87 http://www.ijbst.fuotuoke.edu.ng /81
https://doi.org/10.5281/zenodo.15326448 ISSN 2488-8648

Methods

Monthly temperature data from 1993 to 2023 was obtained from the Nigerian Meteorological Agency (NIMET). The data was thoroughly cleaned and organized by month and year to ensure consistency. Linear regression and Mann-Kendall tests were used to calculate the trend analysis and the yearly temperature data to detect patterns in the mean, maximum, and minimum temperatures over time. To better understand temperature distribution, a boxplot was created to visualize monthly variations and monthly temperature statistics were calculated.Furthermore, the baseline trends and variability patterns were programmed into the analysis to read and interpret temperature data efficiently. The mean surface temperatures for each decade from 1993 to 2023 were plotted in a bar chart, and the temperature changes between consecutive decades were computed to highlight long-term trends. Additionally, we introduced two CMIP6-based climate scenarios: SSP2-4.5, which projects moderate emissions leading to a global temperature rise of approximately 2.7°C by 2100 with some mitigation efforts; and SSP5-8.5, representing high emissions with minimal mitigation, resulting in temperature increases exceeding 4°C by the end of the century. We incorporated trend analyses with uncertainty bands (±1°C) to project future changes. Natural variability was accounted for by integrating statistical noise modeling to provide a more accurate projection.For the extreme event analysis, a threshold of 34.5°C was set to define extreme heat events. We then analyzed the frequency and intensity of these extreme events across three distinct periods. Annual averages of extreme days were also calculated to better understand the occurrence and intensity of heat extremes over time.To further support the analysis, statistical components were integrated. Linear trends were extracted from historical data to understand long-term shifts, and Monte Carlo simulations were used to generate uncertainty ranges. Period-wise statistical aggregation was performed to capture detailed insights into temperature variability and trends throughout the study period. This comprehensive approach ensures robust analysis and reliable conclusions regarding temperature trends in Port Harcourt. CMIP6 models have limitations in regional climate projections, particularly in capturing local-scale variability and extremes. Their coarse resolution and reliance on global emission scenarios may not accurately reflect localized conditions, leading to uncertainties in temperature and precipitation forecasts. Downscaling and bias correction introduce additional uncertainties

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Study Area

Port Harcourt, the capital of Rivers State, Nigeria, is located along the Bonny River in the Niger Delta. It lies between latitudes 4°45′N and 4°55′N and longitudes 6°55′E and 7°10′E. The city experiences a tropical monsoon climate with high humidity, consistent temperatures (25°C to 33°C), and heavy rainfall ranging from 2,300 to 2,500 mm annually. It has distinct wet (April to October) and dry (November to March) seasons, with peak rainfall between June and September, often causing flooding. Port Harcourt's economy is driven by the oil and gas industry, which has spurred rapid growth and environmental degradation, including pollution from oil spills and gas flaring. Urbanization and deforestation have worsened climate-related vulnerabilities, including flooding and rising temperatures. The population, exceeding 3 million, continues to grow, putting pressure on infrastructure and exacerbating issues like inadequate waste management and housing shortages. Environmental and public health risks from industrial activities and climate change impacts, such as rising temperatures and rainfall variability, further stress the infrastructure and resources of Port Harcourt.

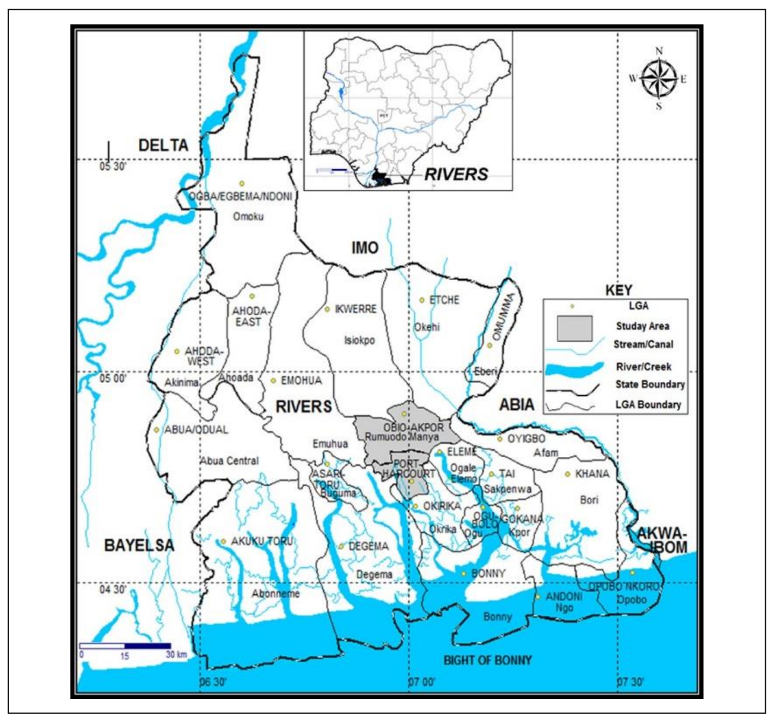

Figure 1: Map of Port Harcourt Source: (Akukwe and Ogbodo , 2015)

International Journal of Basic Science and Technology
April, Volume 11, Number 2, Pages 79 - 87 http://www.ijbst.fuotuoke.edu.ng /82
https://doi.org/10.5281/zenodo.15326448 ISSN 2488-8648

Results and Discussion

Figure 2 shows a statistically significant warming trend in Port Harcourt from 1993 to 2023. The mean temperature rises by approximately 0.0253°C per year, with a highly significant p-value of 0.0025, indicating this increase is not due to random chance. Additionally, the maximum and minimum temperatures are increasing at rates of 0.0463°C and 0.0327°C per year, respectively, with p-values below 0.05, confirming the significance of these trends. The Mann-Kendall test further supports the findings, revealing an increasing trend in mean temperature (p-value = 0.0011), maximum temperature (p-value = 0.0377), and minimum temperature (p-value = 0.0025).

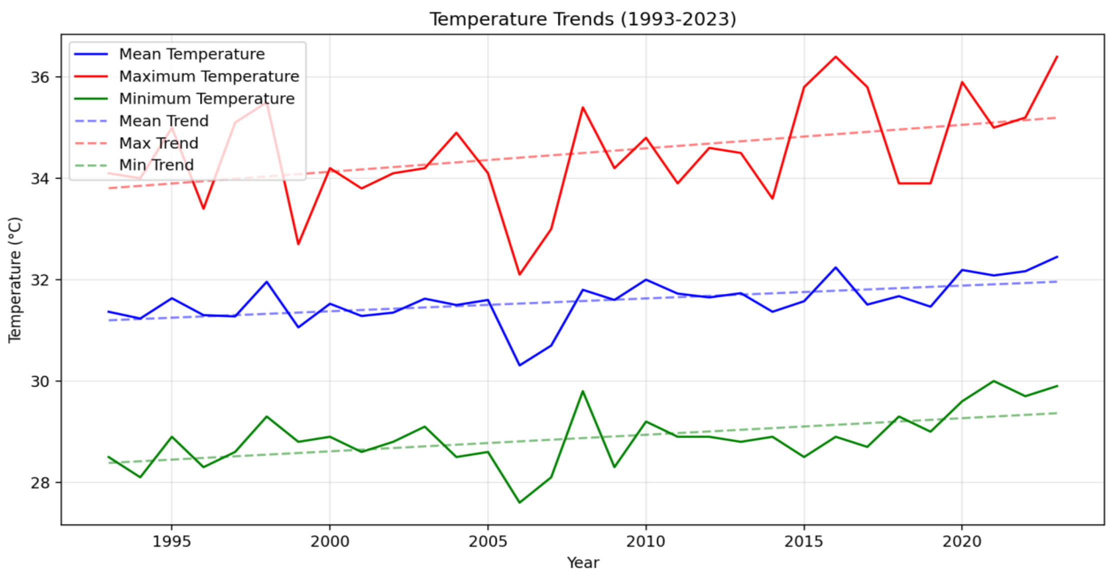

Figure 2: Temperature Trend from 1993 to 2023

The highest temperatures are recorded in February, averaging 34.23°C (± 1.17°C). The coolest period occurs between July and August, with temperatures around 29°C. May experiences the most stable temperatures, showing the lowest standard deviation of 0.44°C, indicating minimal variation. Conversely, December displays the highest temperature variability, with a standard deviation of 0.96°C, reflecting significant fluctuations during this month.

International Journal of Basic Science and Technology
April, Volume 11, Number 2, Pages 79 - 87 http://www.ijbst.fuotuoke.edu.ng /83
https://doi.org/10.5281/zenodo.15326448 ISSN 2488-8648

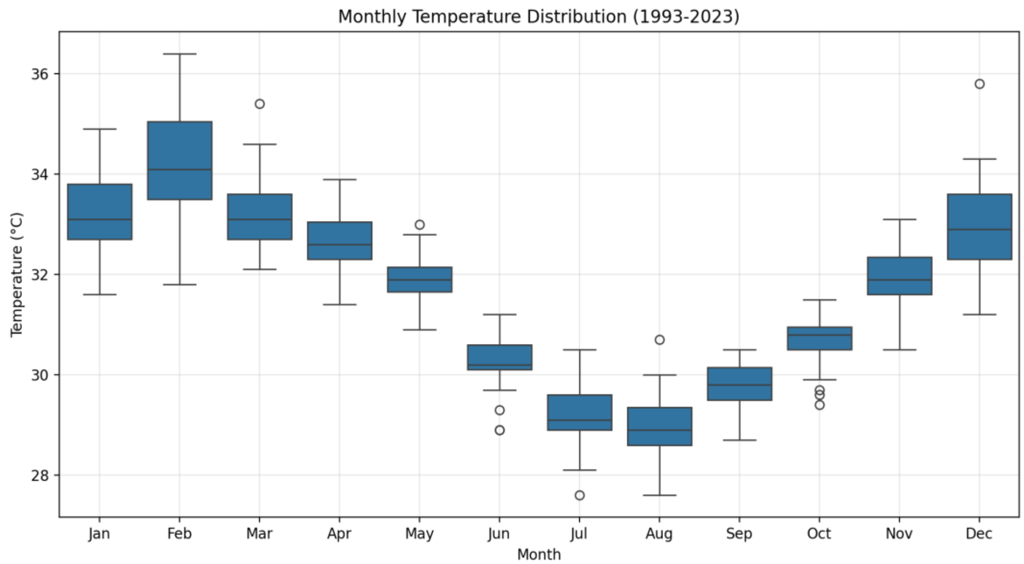

Figure 3: Monthly Temperature Distribution

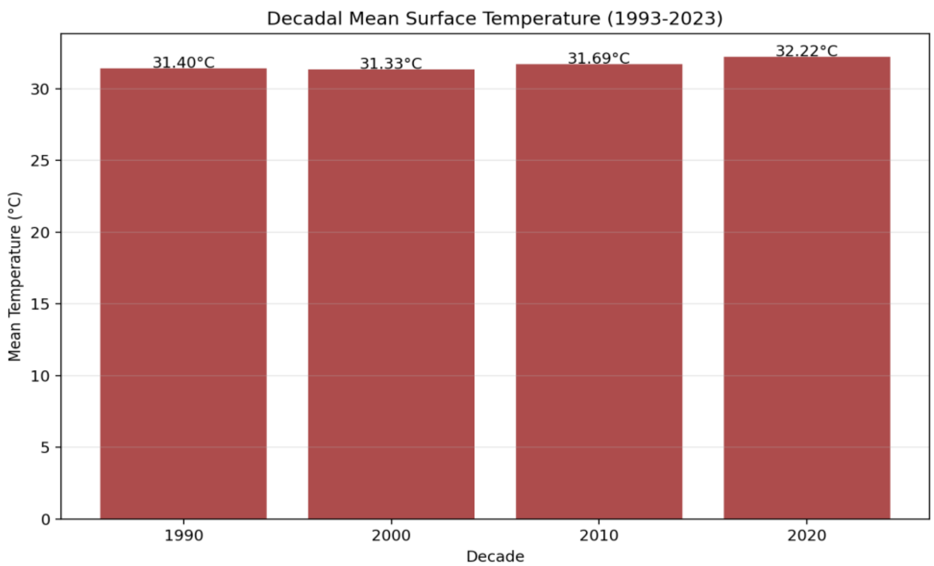

Figure 4: Decadal Mean Surface Temperature

The data reveals an accelerating warming trend, with progressively larger temperature increases across each decade. Notably, the 2020s have experienced the most significant rise, with mean temperatures reaching 32.22°C. Initially, there was a slight cooling of 0.07°C between the 1990s and 2000s, but this was followed by a substantial warming of 0.36°C from the 2000s to the 2010s. This warming trend intensified further, with an even greater increase of 0.53°C from the 2010s to the 2020s. Overall, the findings highlight a clear and accelerating pattern of temperature rise over time

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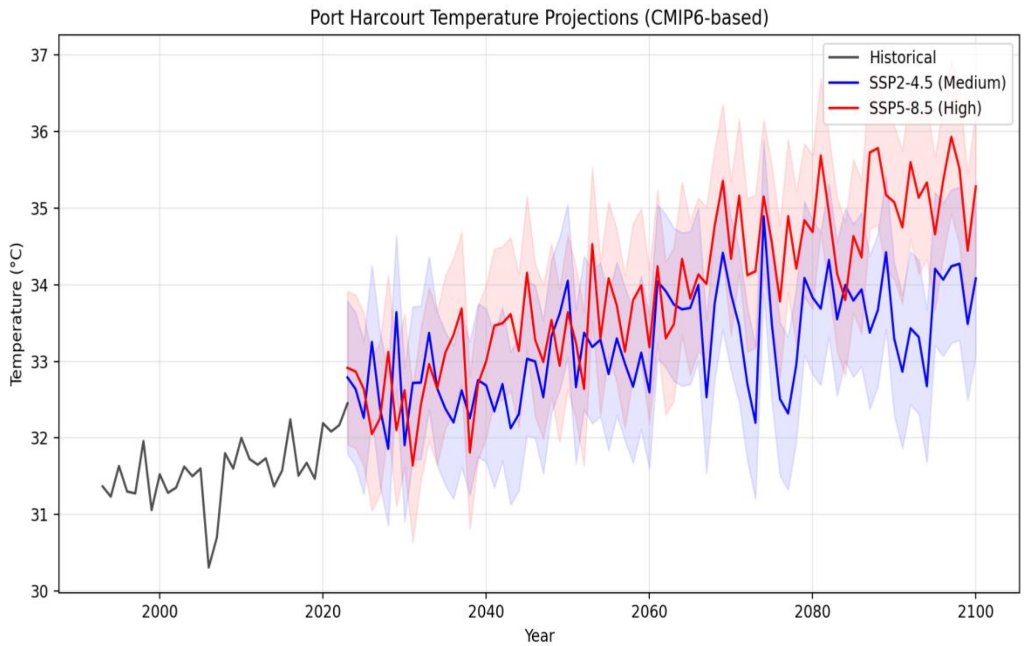

Figure 5: Temperature Projections (CMIP6-based)

The historical data, represented in black, provides a baseline of past temperature trends up to the most recent year. Two future scenarios are projected: SSP2-4.5 (moderate emissions), shown in blue, indicates a steady but moderate increase in temperature, reflecting a scenario where emissions are somewhat controlled. On the other hand, SSP5-8.5 (high emissions), depicted in red, projects a significantly higher warming trend, suggesting more extreme temperature increases if emissions continue to rise at current rates. The shaded areas around each scenario represent uncertainty bands (±1°C), showing the range within which future temperatures is likely to fluctuate, allowing for some variability in the projections.

The projected average temperatures under SSP2-4.5 (moderate emissions) show a gradual increase over time. Between 2023 and 2050, the average temperature is expected to be around 32.7°C with an uncertainty of ±0.5°C. This warming continues into 2051-2080, with an increase to 33.3°C (±0.7°C), and further rises to 33.7°C (±0.5°C) by the end of the century (2081-2100).

In comparison, SSP5-8.5 (high emissions) presents a more pronounced warming trend. For the period 2023-2050, the average temperature is projected to reach 32.9°C (±0.6°C). It escalates to 34.1°C (±0.7°C) from 2051-2080, and reaches 35.1°C (±0.6°C) by 2081-2100. This scenario highlights the potentially severe warming impacts if emissions continue to rise at higher levels.

Both scenarios show a rise in temperatures over time, the high-emission scenario (SSP5-8.5) projects higher end-of-century temperatures relative to the moderate (SSP2-4.5) pathway. This projection underscores the importance of emission reduction strategies to mitigate extreme warming.

April, Volume 11, Number 2, Pages 79 - 87 http://www.ijbst.fuotuoke.edu.ng /85
https://doi.org/10.5281/zenodo.15326448 ISSN 2488-8648

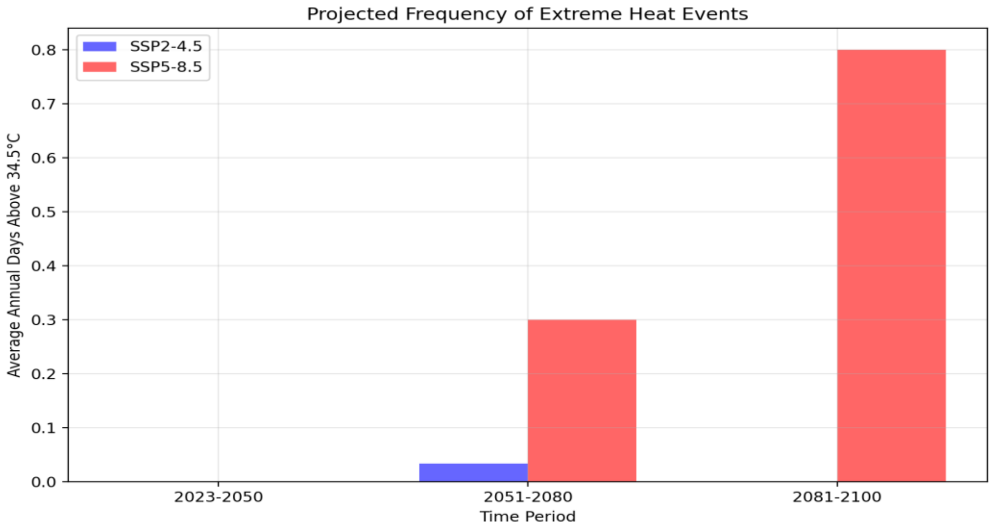

Figure 6: Projected Frequency of Extreme Heat Events

Under the SSP5-8.5 high-emissions scenario, extreme heat events (temperatures exceeding 34.5°C) are projected to become much more frequent. While these events are relatively rare between 2023-2050, they are expected to increase drastically to around 110 days per year by 2081-2100. Additionally, maximum temperatures could approach nearly 36°C, indicating a significant rise in extreme heat occurrences under this scenario.

In contrast, the SSP2-4.5 moderate-emissions scenario shows a less dramatic increase in extreme heat events. Maximum temperatures are expected to stay closer to 34.5°C, with fewer extreme events overall. This scenario also suggests a more stable and less volatile long-term temperature pattern, underscoring the importance of emissions reduction for mitigating extreme temperature events.The difference between scenarios becomes most pronounced after 2050, highlighting the importance of near-term climate action.

The study reveals a statistically significant warming trend in Port Harcourt, Nigeria, between 1993 and 2023. The baseline mean temperature over this period is approximately 32.22°C. A decadal analysis shows an acceleration in temperature increase, with the largest rise occurring between the 2010s and 2020s (+0.53°C), highlighting an ongoing climate change impact. The linear regression analysis reinforces this, indicating an average increase of 0.025°C per year in mean temperatures, with maximum and minimum temperatures also rising by 0.046°C and 0.033°C per year, respectively. All trends were statistically significant, as confirmed by the Mann-Kendall Test. Future projections based on two emission scenarios (SSP2-4.5 and SSP5-8.5) indicate a continuation of this warming trend. Under the high-emissions pathway (SSP5-8.5), extreme heat events (>34.5°C) are expected to become more frequent, with up to 110 days of extreme heat per year by the end of the century, compared to fewer extreme events under the moderate emissions scenario (SSP2-4.5). These findings underline the urgency of emission reduction strategies to limit extreme temperature increases and their associated risks.

Buba and Ibrahim (2018) indicate a general increase in temperatures across northern Nigeria since the 1950s, with urban areas experiencing marked warming. However, specific decadal warming trends of 0.02-0.05°C per year in Kano. This is comparable to the warming observed in Port Harcourt, particularly in terms of the increasing maximum and minimum temperatures. Isioye *et al.* (2022) analyzed temperature changes in Abuja and confirmed the existence of a warming trend consistent with global patterns of climate change. Their findings on extreme heat events projected under future scenarios mirror the results of this study, as the high-emission scenario predicts a sharp increase in extreme heat occurrences, particularly in the last half of the century.Atuma *et al.* (2023), investigating temperature trends in Southern Nigeria, reported a slower rate of temperature increase in coastal regions, particularly in the Niger Delta. They argued that localized factors, including the cooling effect of water bodies and vegetation, may be moderating the temperature rise. While this study highlights significant warming in Port Harcourt, a coastal city in the Niger Delta, the faster rate of temperature increase here might be attributed to urbanization and industrial activities that exacerbate

April, Volume 11, Number 2, Pages 79 - 87 http://www.ijbst.fuotuoke.edu.ng /86
https://doi.org/10.5281/zenodo.15326448 ISSN 2488-8648

warming through the urban heat island effect. Animashaun *et al.* (2023) examined temperature variability in some parts of Northern Nigeria and found relatively stable temperature increases, with fewer occurrences of extreme heat events compared to what is projected for the Niger Delta in this study. This variation can be attributed to different local climate systems, land-use changes, and urbanization patterns in the north versus the south. Comparative studies across Nigeria reveal regional variations in warming trends. In Northern Nigeria, Buba and Ibrahim (2017) identified significant temperature increases since the 1950s, particularly in urban areas like Kano. In Abuja, Isioye *et al.* (2020) reported rising land surface temperatures linked to urban heat island effects. Conversely, Atuma *et al.* (2023) observed a slower temperature increase in the Niger Delta, attributing it to moderating influences of water bodies and vegetation. Animashaun *et al.* (2023) noted relatively stable temperatures in parts of Northern Nigeria, with fewer extreme heat events compared to projections for the Niger Delta. These findings underscore the importance of localized climate analyses.

Conclusion

This study analyzed 30 years of temperature data in Port Harcourt, revealing a significant increase in both minimum and maximum temperatures, aligning with global warming trends. Seasonal variations were evident, with more pronounced temperature shifts during the dry season. Employing CMIP6 models, future climate scenarios were projected, indicating continued temperature escalation, particularly under high-emission scenarios. These projections suggest potential adverse effects on public health, agriculture, and critical infrastructure, as rising temperatures could intensify heat stress, reduce crop yields, and strain energy systems. Integrating climate adaptation into policy and planning is essential, focusing on resilient infrastructure, sustainable urban designs, and enhanced public health systems to mitigate heat-related risks. Adaptation strategies should prioritize proactive measures to reduce vulnerability and ensure sustainable development in the face of climate change. The findings underscore the urgency of adopting robust climate adaptation strategies to reduce vulnerability to future climate impacts. Heightened public awareness on the health implications of extreme heat and the promotion of sustainable agricultural practices are crucial. Collaborative efforts between policymakers, scientists, and stakeholders are vital to addressing these emerging challenges and ensuring a sustainable and climate-resilient future for Port Harcourt.

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April, Volume 11, Number 2, Pages 79 - 87 http://www.ijbst.fuotuoke.edu.ng /87
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