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Climate Extremes in Port Harcourt: Modeling Rainfall Anomalies using GCMs and RCMs.

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Abstract

The study analyzes long-term rainfall trends, identifies seasonal variability and extreme weather events, assesses rainfall anomalies and drought frequency, and compares the accuracy of Global Climate Models (GCMs) and Regional Climate Models (RCMs) in predicting localized conditions for more reliable regional climate adaptation planning. The study utilized monthly rainfall data from NIMET, categorized into meteorological seasons (DJF, MAM, JJA, SON). Descriptive statistics and anomalies were computed to analyze long-term rainfall trends. Droughts and extreme rainfall events were identified, and Global Climate Models (GCMs) and Regional Climate Models (RCMs) were compared to observed data. The study revealed a slight annual decrease in rainfall of approximately 13.57 mm per year, with a moderate p-value (0.0858) and low R-squared (0.0983), indicating high variability. Peak rainfall occurred between May and September, while drier months were December and January. Rainfall anomalies showed maximum positive and negative values of 281.02 mm (August 2002) and -243.29 mm (September 2019), respectively. Extreme rainfall events increased slightly by 0.04 per year, with 21 events surpassing the 95th percentile (2002.90 mm). The longest droughts lasted two months, notably from January to February 2016 and 2018. Regional Climate Models (RCMs) closely matched observed data, while Global Climate Models (GCMs) exhibited greater variability. The study identified increased extreme rainfall events and recurring drought periods, emphasizing the need for climate adaptation strategies. The study recommends regional climate models (RCMs) for future planning and implementing Water Sensitive Urban Design (WSUD) to mitigate flooding and extreme weather impacts in coastal cities like Port Harcourt.

Keyword: Anomalies, Rainfall, Climate Change, GCMs, RCMs.

INTRODUCTION

Climate change has emerged as one of the most pressing environmental challenges of the 21st century, driving widespread changes in weather patterns at both global and regional scales (IPCC, 2021). Over the past decade, research has demonstrated a strong correlation between rising rainfall and the increased frequency and intensity of extreme weather events, such as heatwaves, floods, and droughts (Herring *et al.*, 2022). These climatic shifts not only influence ecosystems (Akayinaboderi *et al.*, 2024; Saliu *et al.*, 2023; Raimi *et al.*, 2022a, b; Raimi *et al.*, 2021; Olalekan *et al.*, 2021; Okoyen *et al.*, 2020; Raimi *et al.*, 2019a, b; Olalekan *et al.*, 2019), but also have direct consequences on agriculture (Suleiman *et al.*, 2019; Raimi *et al.*, 2019a, b), water resources, and public health (Oweibia *et al.*, 2024; Morufu *et al.*, 2021; Raimi *et al.*, 2019c; Raimi *et al.*, 2018), particularly in developing regions with limited adaptive capacity (Mora *et al.*, 2018). As a result, unpredictable and severe weather patterns are becoming more common, posing serious threats to the socio-economic stability of vulnerable communities (Morufu *et al.*, 2022; Diffenbaugh and Burke, 2019; Odubo and Raimi, 2019). Furthermore, without significant reductions in greenhouse gas emissions, recent models suggest that these extremes will become more frequent and intense (Morufu *et al.*, 2021; Schiermeier, 2018). Given the growing vulnerability of many regions, particularly coastal cities, studying climate extremes has become increasingly crucial. Coastal areas, such as Port Harcourt, are especially prone to the adverse effects of climate change, including rising sea levels, increased precipitation, and more frequent extreme storms (Morufu *et al.*, 2021; Hoegh-Guldberg *et al.*, 2019; Raimi *et al.*, 2018). This combination of factors heightens the likelihood of flooding, heat stress, and other climate-induced hazards that strain infrastructure, ecosystems, and local economies (Morufu *et al.*, 2022; Odubo and Raimi, 2019; Kulp and Strauss, 2019). Thus, understanding the trend of rainfall anomalies in cities like Port Harcourt is essential for developing effective adaptation strategies, improving resilience, and mitigating the worst impacts of climate change. Recent studies underscore the need for climate-resilient infrastructure and disaster preparedness, especially in vulnerable regions like coastal cities (Odubo and Raimi, 2019; Nicholls *et al.*, 2021; Morufu *et al.*, 2022). To predict and understand climate extremes, scientists have increasingly turned to advanced climate modeling techniques. Two prominent approaches are Global Climate Models (GCMs) and Regional Climate Models (RCMs), which simulate climate variability and project future changes. GCMs, operating on a global scale, capture the complex interactions between the atmosphere, oceans, land surfaces, and ice. While GCMs have been instrumental in providing insights into global climate trends, they often lack the spatial resolution necessary for capturing regional climate dynamics accurately. This limitation is effectively addressed by RCMs, which downscale climate projections to finer spatial resolutions, providing more localized climate information (Giorgi, 2019).

Specifically in West Africa, where local topography, land-use changes, and coastal influences significantly affect climate variability, RCMs offer crucial insights into rainfall patterns, temperature extremes, and small-scale atmospheric circulations (Ruosteenoja and Räisänen, 2023). Thus, RCMs are particularly important for regional climate studies when assessing the impacts of climate change on ecosystems, agriculture, and infrastructure. At the core of these studies, rainfall anomalies serve as key indicators of climate variability, representing deviations from long-term average values. Such deviations, whether positive or negative, result from both natural processes like the El Niño-Southern Oscillation (ENSO) and anthropogenic climate change (Alizadeh *et al.*, 2022). These rainfall anomalies have far-reaching consequences, particularly when sustained over time. For instance, prolonged heatwaves can lead to mass die-offs of plants and animals, especially in tropical regions where biodiversity is already under stress (Akayinaboderi *et al.*, 2024; Saliu *et al.*, 2023; Costa *et al.*, 2023; Raimi *et al.*, 2022a, b). Likewise, rainfall anomalies, whether excessive or drought, exacerbate water scarcity, lead to severe flooding, and degrade habitats (Franchi *et al.*, 2024).

These impacts are particularly acute in coastal ecosystems, where shifting precipitation patterns threaten the stability of mangroves, wetlands, and coral reefs (Okoyen *et al.*, 2020; Hoegh-Guldberg *et al.*, 2019). Moreover agriculture, a critical sector in many African economies remains highly sensitive to climate anomalies. In Nigeria, for example, shifts in rainfall patterns have already contributed to more frequent droughts in the north and increased rainfall in the south, including the Niger Delta. As a result, these extremes disrupt planting cycles, reduce crop yields, and increase the risk of food insecurity (Odubo and Raimi, 2019; Morufu *et al.,* 2022; Grigorieva *et al.,* 2023). Additionally, in urban areas like Port Harcourt, heavy rainfall and flooding often damage essential infrastructure, while prolonged heatwaves strain energy grids, leading to power shortages (Gift and Olalekan, 2020; Gift *et al.,* 2020; Khan *et al.,* 2024). At the same time, rising sea levels and increased precipitation further exacerbate coastal erosion, saltwater intrusion, and infrastructure collapse (Fouad *et al.,* 2024).

West Africa, recognized as one of the most vulnerable regions to climate change, is projected to experience more frequent and intense weather extremes in the coming decades. Several studies using GCMs and RCMs have highlighted increasing rainfall variability and a greater likelihood of heatwaves, prolonged dry spells, and intense rainfall events (Nasidi *et al.,* 2024; Ayanlade *et al.,* 2022). These projected changes have severe socio-economic and environmental impacts, especially in countries like Nigeria, where climate resilience remains low. In particular, the Niger Delta, with its unique coastal and wetland ecosystems, is highly susceptible to these climate extremes. For example, increased rainfall variability has led to more frequent flooding, coastal erosion, and water pollution, exacerbating existing environmental challenges in the region (Raimi and Sawyerr, 2022; Raimi *et al.,* 2022c, d, e; Echendu *et al.,* 2022; Olalekan *et al.,* 2022; Raimi *et al.,* 2023; Kader *et al.,* 2023; Clinton-Ezekwe *et al.,* 2024). Despite these findings, there remains a notable gap in the literature, particularly concerning the application of regional climate models to assess rainfall variability and anomalies in coastal cities like Port Harcourt. While previous studies have provided important insights into climate extremes in West Africa, they often lack the localized focus necessary to inform effective adaptation strategies for vulnerable regions. Thus, this research seeks to address that gap by focusing on RCMs in Port Harcourt.

METHODOLOGY

Study Area

Port Harcourt, the capital of Rivers State, Nigeria, is strategically located in the Niger Delta region between latitude 4°45'N and 4°60'N and longitude 6°50'E and 7°10'E, about 60 kilometers from the Atlantic coast (see figure 1 below). Positioned along the Bonny River, the city is a key hub for Nigeria's oil and gas industry. Due to its proximity to offshore oil fields, Port Harcourt has undergone significant industrial and commercial expansion. The city has a tropical monsoon climate, with high temperatures ranging from 25°C to 30°C, heavy rainfall, and high humidity. The rainy season lasts from April to October, with peak rainfall in July and September, and the city receives an average of 2,400 mm of rain annually (NIMET, 2020). Economically, Port Harcourt is vital to Nigeria due to its oil and gas operations. However, rapid urbanization has created challenges such as inadequate housing, strained infrastructure, and environmental degradation from oil spills and gas flaring (Nwilo and Badejo, 2005; Raimi *et al.,* 2022c, d, e; Olalekan *et al.,* 2022; Raimi and Sawyerr, 2022; Raimi *et al.,* 2023; Clinton-Ezekwe *et al.,* 2024). Port Harcourt's economic significance and environmental vulnerabilities make it a critical yet challenging region in Nigeria.

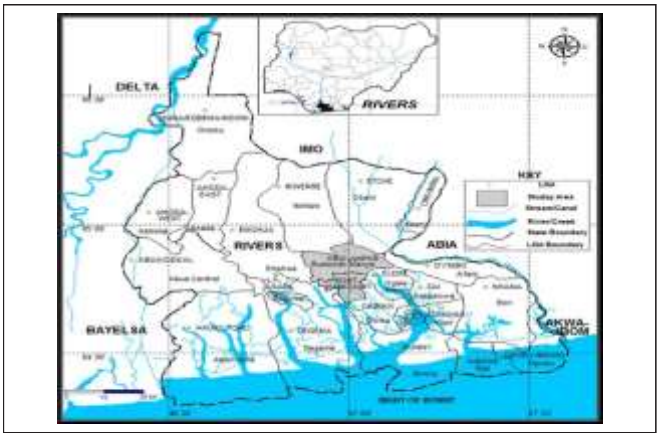

Figure 1: Map of Port Harcourt, showing study location
Source: Akukwe and Ogbodo (2015)

Method

The monthly rainfall data was collected from the Nigerian Meteorological Agency (NIMET), cleaned, and organized by month and year. The data was grouped into standard meteorological seasons - DJF (December-February), MAM (March-May), JJA (June-August), and SON (September-

November). Descriptive statistics, including averages and standard deviations, were calculated to establish baseline climate conditions. Rainfall anomalies were computed by comparing monthly rainfall with historical averages to identify deviations. Drought months, defined as months with rainfall below 10 mm, were flagged to track periods of low precipitation. To process and analyze rainfall variability and trends, Pandas and NumPy were employed to compute monthly averages, anomalies, and key descriptive statistics from the observational data. These tools provided efficient data manipulation and numerical operations essential for temporal analysis. To enhance interpretability, Seaborn was utilized to generate heatmaps visualizing spatiotemporal patterns of rainfall anomalies across multiple years, while Matplotlib served as the backbone for generating all graphical outputs, including time series and trend plots. Additionally, custom Python functions were scripted to identify drought periods using threshold-based logical conditions, offering flexibility in defining drought criteria suitable for the study area.

Annual and seasonal rainfall trends were systematically analyzed to detect long-term changes and infer climate variability signals. In parallel, climate modeling outputs were incorporated to contextualize the observational findings. Global Climate Models (GCMs) were selected for their robust ability to simulate large-scale atmospheric circulation patterns and greenhouse gas-induced climate dynamics on a planetary scale. These models provide essential boundary conditions and historical climate baselines. However, their coarse spatial resolution limits their capacity to represent regional or localized features accurately. To address this, Regional Climate Models (RCMs) which nest within GCM outputs were also integrated. RCMs offer finer spatial resolution, making them better suited for assessing the spatial heterogeneity of rainfall and capturing mesoscale phenomena, especially in complex terrains like those found in West Africa.

The integration of GCMs and RCMs allowed for a more comprehensive understanding of climatic drivers behind rainfall trends and droughts. Nonetheless, several limitations were encountered. GCMs often carry systemic biases when downscaled to local conditions, potentially distorting model outputs if not bias-corrected. Although RCMs improve spatial precision, they are still dependent on the quality and accuracy of the GCM boundary inputs. Additionally, observational rainfall datasets used for validation were limited in spatial coverage and completeness, particularly in remote regions where ground stations are sparse or data quality is inconsistent. These constraints may affect the reliability of trend detection and the robustness of model-observation comparisons, thereby necessitating cautious interpretation of results.

RESULTS AND DISCUSSION

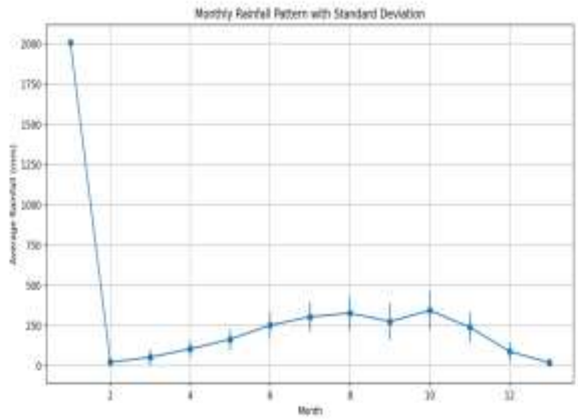

Figure 2: Monthly Rainfall Pattern

The annual trend analysis revealed a slight downward slope in rainfall over the study period (figure 2), decreasing by approximately 13.57 mm per year. However, the moderate p-value (0.0858) and low R-squared (0.0983) indicate significant variability in the data, suggesting that while the overall trend points to a slight decrease, short-term fluctuations may obscure clear long-term patterns. Seasonal patterns were evident, with rainfall peaking between May and September, showing higher averages and greater variability. In contrast, lower rainfall occurred during the early and late months of the year, particularly in December and January, when both mean values and standard deviations were smaller, reflecting more stable and drier conditions.

Figure 3 illustrates the monthly rainfall anomalies across multiple years, showing deviations from the average rainfall. The colors in the heatmap represent the extent of these deviations, with red indicating above-average rainfall and blue indicating below-average rainfall.

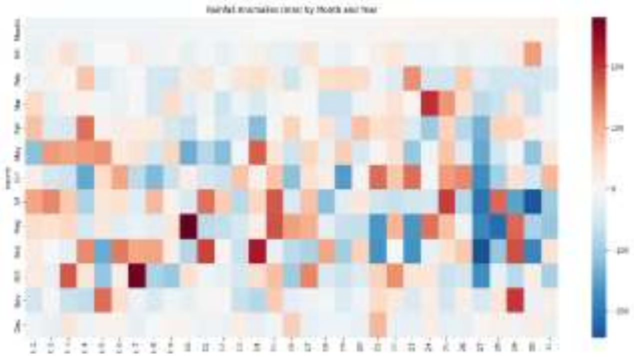

Figure 3: Monthly Rainfall Anomaly Patterns *(1993-2023)*

Notably, the maximum positive anomaly recorded was around 281.02 mm, reflecting an unusually wet period, while the most significant negative anomaly was approximately -243.29 mm, indicating a particularly dry month. The extreme positive anomaly in August 2002 suggests that this month experienced significantly more rainfall than typical, possibly due to anomalous weather conditions like intense tropical storms or shifts in atmospheric circulation patterns. Conversely, the extreme negative anomaly in September 2019 points to a severe drought, likely caused by a prolonged absence of rain or climate events like El Niño, which can disrupt regular rainfall patterns.

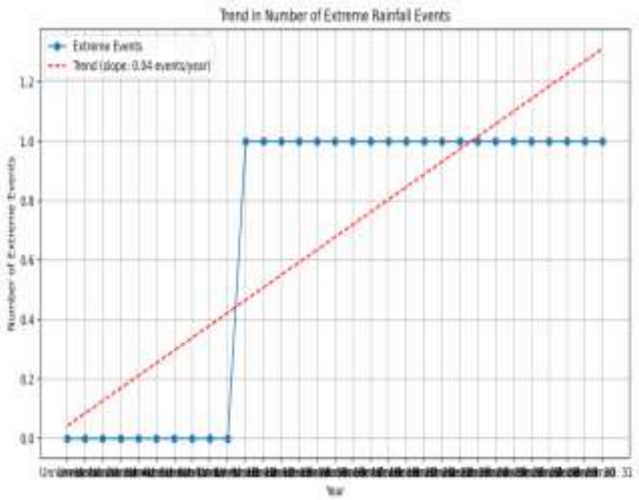

Figure 4: Extreme Rainfall Events

The result in figure 4 reveals distinct seasonal patterns, highlighting significant anomalies with periods of above-average and below-average rainfall. Over the study period, extreme rainfall events showed a slight upward trend at 0.04 per year. Twenty-one (21) extreme rainfall events, exceeding the 95th percentile threshold of approximately 2002.90 mm, were recorded. The upward trend in extreme rainfall suggests increasing weather variability, potentially linked to broader climate changes.

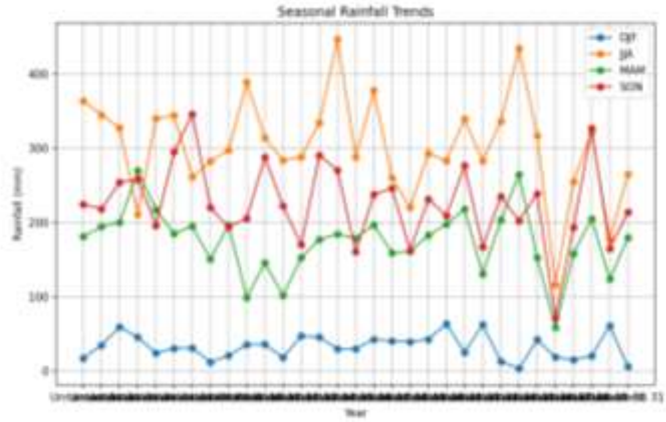

Figure 5: Seasonal Rainfall Trends

Seasonal rainfall using standard meteorological groups (DJF, MAM, JJA, SON) (Figure 5). These plots indicate the expected variations throughout the year, with lower rainfall during the dry season (DJF) and peak rainfall during the wet periods (typically JJA and SON). Such behavior is consistent with the typical tropical monsoon patterns.

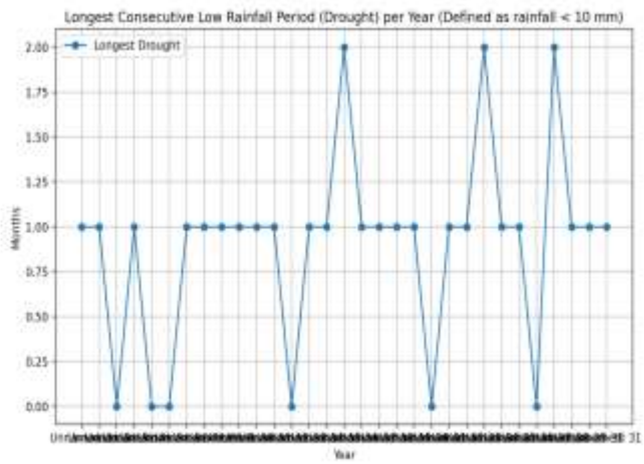

Figure 6: Drought Analysis

The results (figure 6) indicate that the longest consecutive drought periods observed lasted for two months, with rainfall falling below the 10 mm threshold. Specifically, droughts were recorded from January to February in both 2016 and 2018. December and January emerged as the months with the highest frequency of drought occurrences. In general, the drought analysis, which defined droughts as periods with less than 10 mm of rainfall, revealed that most years experienced short drought episodes, typically lasting just one month. However, there were notable instances of extended droughts, with some periods extending up to two consecutive months.

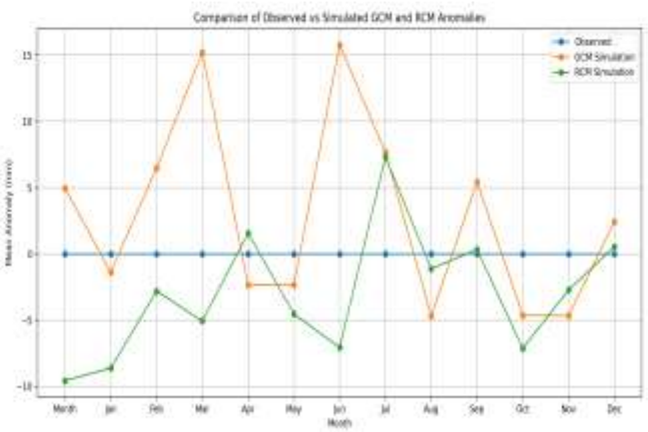

Figure 7: Simulated GCM and RCM Anomalies

The visual display of anomaly distributions across months and years highlights areas with strong red or blue shades (Figure 7), representing months with significantly above- or below-average rainfall, respectively. This visual pattern reveals seasonal variations, extreme events, or gradual shifts in rainfall over time. For the simulated model outputs, synthetic anomalies were generated to emulate the results from Global Climate Models (GCMs) and Regional Climate Models (RCMs). The GCM simulation incorporated more noise, indicating greater variability or uncertainty in global models, while the RCM simulation, with less noise, stayed closer to observed values, suggesting better representation of localized conditions. When comparing the observed anomalies with the simulated outputs from GCMs and RCMs, all series reflected similar seasonal trends, demonstrating that the models captured the seasonal cycle. However, the GCM showed larger fluctuations, suggesting a tendency to overestimate rainfall variability. In contrast, the RCM aligned closely with the observed data, indicating its potential reliability for regional predictions. Ogunbode *et al.* (2022) similarly observed declining rainfall trends, particularly in southern Nigeria, though variations exist across regions. These findings complement the results of this study, which identified a subtle downward trend in annual rainfall, emphasizing the need to consider local variations when analyzing rainfall patterns across the country. This regional variability is further supported by the seasonal rainfall patterns identified by Ishaku *et al.* (2024), who noted a bimodal distribution with primary rainfall peaks in June-August (JJA) and secondary peaks in September-November (SON). The consistency between these findings and the established monsoon cycle across West Africa validates the influence of the Intertropical Convergence Zone (ITCZ) on rainfall patterns, highlighting the intricate relationship between seasonal shifts and precipitation trends. As the analysis transitions to extreme rainfall events, it becomes evident that the slight upward trend in these occurrences, an increase of 0.04 events per year points to a rising frequency of intense weather. This pattern aligns with global trends tied to climate change, which are driven by increased atmospheric temperatures. As the atmosphere retains more moisture, precipitation events become more severe. Audu *et al.* (2021) similarly noted a rise in extreme rainfall events in Nigeria, attributing this shift to climate change's impact on atmospheric dynamics. This increasing intensity corresponds with the Intergovernmental Panel on Climate Change (IPCC), which foresees more frequent and intense precipitation events as global temperatures rise.

In addition to extreme rainfall, the analysis of drought events reveals an unsettling pattern. The identification of consecutive drought periods in 2016 and 2018, as well as shorter one-month droughts, mirrors findings by Ogunrinde *et al.* (2022), who observed similar trends during the dry season (DJF) in Nigeria. However, the drought periods raise significant concerns about prolonged dry spells, potentially exacerbated by climate change. This emerging pattern of extended droughts could pose severe risks to agricultural productivity and water security, especially in regions dependent on seasonal rainfall, further emphasizing the importance of addressing these challenges through sustainable resource management. A crucial component of this study involved comparing rainfall projections from Global Climate Models (GCMs) and Regional Climate Models (RCMs). While GCMs offer insights into large-scale climate patterns, they often struggle to capture local-scale processes due to their coarse spatial resolution. These limitations have been well-documented, with Sylla *et al.* (2016) also identifying the challenges GCMs face when projecting localized rainfall patterns in West Africa. In contrast, the RCMs used in this study, with their higher resolution, provided more accurate and reliable projections, closely aligning with observed rainfall data. This finding is consistent with the conclusions of Wu *et al.* (2020), who emphasized the value of RCMs in offering improved precision for regions with complex climate systems, such as Nigeria. The greater accuracy of RCMs in capturing localized weather conditions reinforces their importance for making informed decisions in urban and agricultural planning. These findings underscore the real-world implications for urban planning, water management, and policy development in regions like Port Harcourt. The observed downward trend in annual rainfall, combined with the rising frequency of extreme weather events, highlights the need for more robust flood control measures and climate-resilient infrastructure. As urban areas continue to expand, it is critical to prioritize improvements in drainage systems, flood zoning, and the construction of resilient buildings to better cope with the uncertainties posed by future climate patterns. In parallel, the increasing incidence of droughts poses significant challenges to agriculture and water availability, necessitating sustainable water management practices and the adoption of advanced irrigation technologies to safeguard food and water security. Ultimately, scientific insights into policy frameworks will be essential for addressing the dual challenges of flooding and drought. Policymakers must invest in climate adaptation strategies, including strengthening coastal defenses and adopting climate-smart agricultural practices. These measures will protect livelihoods, ensure sustainability, and mitigate the impacts of changing rainfall patterns on vulnerable communities. In conclusion, this study's comprehensive rainfall trend analysis, set against the backdrop of broader research in Nigeria, reinforces the urgent need for proactive climate adaptation strategies to safeguard urban and rural regions in the face of increasing climate variability.

CONCLUSION

This study identified key trends and variability in rainfall patterns over the study period, revealing a slight downward trend in annual rainfall and an increase in extreme rainfall events. Seasonal fluctuations were prominent, with the wettest periods from May to September and drier conditions from December to January. The upward trend in extreme rainfall aligns with climate change projections and highlights growing weather variability. Recurring droughts and rainfall anomalies further contribute to understanding the region's rainfall dynamics. The findings emphasize the need for improved climate adaptation strategies, particularly in urban areas like Port Harcourt. Accurate regional models, such as RCMs, are vital for reliable climate planning due to their capacity to capture localized conditions. Implementing Water Sensitive Urban Design (WSUD) can mitigate the effects of extreme weather, especially flooding linked to rising sea levels and intensified storms. Stakeholders must prioritize investments in climate-resilient infrastructure and policies to support sustainable urban development and reduce the vulnerability of coastal cities to climate change. Future research should focus on how changing rainfall patterns affect agriculture and water resources, assess the effectiveness of climate adaptation strategies like WSUD, and examine the interaction between sea level rise and extreme weather in coastal regions for comprehensive climate risk assessments.

Significant Health Statement

The observed changes in rainfall patterns, including increased extreme rainfall events and recurring droughts, have significant public health implications. Extreme rainfall and flooding can exacerbate waterborne diseases, including cholera and typhoid, due to contamination of drinking water sources. Increased moisture and prolonged wet conditions also create favorable environments for vector-borne diseases such as malaria and dengue fever. Conversely, recurrent droughts can reduce water availability, leading to poor sanitation, food insecurity, and increased risk of malnutrition. These climatic fluctuations underscore the need for improved public health preparedness, early warning systems, and resilient infrastructure to mitigate climate-related health risks in urban areas like Port Harcourt. Thus, effective climate adaptation strategies, such as Water Sensitive Urban Design (WSUD), can help manage urban flooding and water quality, reducing disease outbreaks linked to extreme rainfall events. Additionally, investments in climate-resilient water supply systems and sanitation infrastructure are essential to safeguard public health during droughts and flooding. Policymakers must prioritize integrating climate projections into health planning to anticipate and mitigate the impacts of changing rainfall patterns. Future research should assess how shifting precipitation trends affect disease patterns and healthcare systems, ensuring evidence-based interventions that enhance public health resilience in the face of climate change.

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