EVALUATION OF PROJECTED DISTRIBUTION OF NEW URBAN CLIMATES AND ITS IMPLICATIONS FOR NIGERIA

BY

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PhD/SPS/FT/2019/11128

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THESIS SUBMITTED TO THE POSGRADUATE SCHOOL, FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA, NIGERIA, IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF DEGREE OF DOCTOR OF PHILOSOPHY (PhD) IN CLIMATE CHANGE AND HUMAN HABITAT

OCTOBER, 2024

DECLARATION

I, hereby declare that this thesis titled: "**Evaluation of Projected Distribution New Urban Climate and its Implications for Nigeria**" is a collection of my original research work and it has not been presented for any other qualification anywhere. Information from other sources (published or unpublished) has been duly acknowledged.

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SIGNATURE AND DATE

CERTIFICATION

The thesis titled "**Evaluation of Projected Distribution of New Urban Climate and its Implications for Nigeria**" by ASONIBARE, Femi Oluwatosin (PhD/SPS/FT/2019/11128) meets the regulations governing the award of degree of PhD of the Federal University of Technology Minna, and it is approved for its contribution to scientific knowledge and literacy presentation.

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ABSTRACT

Responding to the threats of climate change by cities requires relevant actions that will communicate future climate conditions in a reliable and effective manner for sustainable and transformational climate actions. Given that the population of urban areas in Nigeria continues to rise and that changes in climate conditions continue to have profound implications on urban residents, a better understanding of the implication of these changes has informed this study. The study presents the current and future climatic conditions of major Nigerian cities in the past by using the analogy approach (climate similarity) and presents the implications for future sustainable city related actions. The future climates of the cities were identified in the past under two representative concentration pathways RCP4.5 (mitigation scenario), RCP8.5 (emissions continuing to rise throughout the 21st century). The climate similarity was calculated using data set from coupled model inter-comparison project-5 (CMIP5), a downscaled and biased-corrected projections of future climate for total monthly precipitation and average temperature (running mean of 2030s and 2050s) and a modified R similarity script. The study revealed that the climate of Nigerian cities in the current (average of 2030s) and future (average of 2050s) periods will be similar to the historical (1971 to 2000) climatic condition of another place on the globe based on the similarity scores. The new places with similar climate conditions are to the south of the corresponding cities (indicating warming) and within the neighbourhood of longitude (10°W to 20°E) in the tropics. The similarity scores in the mitigated scenario for the 2030s climate are; 0.81, 0.78, 0.77, 0.80, and 0.74, while the unmitigated scenarios are; 0.79, 0.64, 0.76, 0.68, 0.75 for Abuja, Lagos, Makurdi, Benin, and Port Harcourt respectively. This implies that the high similarity values of 0.81 and 0.79 for the city of Abuja presents a climatic condition most similar to Kuje and Teungo while the city of Kano with low similarity values of 0.64 and 0.68 presents a drastic change in climate conditions which is an indication climate novelty. Similarly, the results for similarity scores for the 2050s are; 0.8 0, 64, 0.74, 0.67, 0.71 if climate mitigation continues and 0.7, 0.61, 0.74, 0.69, 0.69 for the unmitigated scenario. Also, the city of Abuja in the 2030s has a 2.59 ^{o}C increase in temperature when compared to the historical period while the indices shows that the highest warming in minimum temperature is in Abuja and Kano. This significantly increasing trend in the hot and warm indices and the decreasing trends in the occurrence of cool days is an indication of warming for the cities. These are indications of increased exposure of the cities to climate impacts such as heatwaves, and for Kano city, water scarcity. The results implies that despite the use of a highly optimistic climate change scenario (RCP 4.5), the climate conditions of the cities will change or shift to such a great extent that they will resemble more closely the conditions of another place entirely. Drawing from the interaction between the cities and their analogues, the study advances the urban climate resilience literature by illuminating the future impacts of different climate scenarios on urban areas. To develop a climate sustainable city, a mix of infrastructure and behavioural change such as the incorporation of climate considerations into urban designs and policies to enhance human thermal comfort are required. The findings guides the understanding and application of the analogue approach and developed a more relate-able communication approach for climate change awareness by simplifying the complex abstracts and scientific projections of climate into personal experiences. While future research might apply qualitative studies and additional data to support the analogue results, the findings presents the use of analogue approach into environmental issues in Nigeria and other West African countries in accordance to sustainable city goals (SDG 11).

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LIST OF ABBREVIATIONS

Abbreviations	
AMIP	Atmospheric Model Inter-comparison Project
CCAFS	Climate Change, Agriculture and Food Security
CMIP 5	Coupled Model Inter-comparison Project Phase 5
CORDEX	Coordinated Regional Downscaling Experiment
CRU	Climate Research Unit Gridded dataset
CSDI	Cold Spell Duration index
CSIRO MK3	Commonwealth Scientific and Industrial Research Organisation
ESMs	Earth system models
ETCCDMI	Expert Team for Climate Change Detection Monitoring and Indices
GCMs	Global Climate Models
GEOS	Goddard Earth Observing System
GHGs	Greenhouse gases
HadGEM3	Hadley Centre Global Environment Model 3
IPCC	Intergovernmental Panel on Climate Change
MIROC	Model for Interdisciplinary Research on Climate
NASA	National Aeronautics and Space Administration
NCCC	National Council on Climate Change
RCMs	Regional Climate Models
RCPs	Representative Concentration Pathways
SEDs	Standardized Euclidean distances
SRES	Special Report on Emissions Scenarios
UNHABITAT	United Nations Human Settlements Programme

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

Within the lifetime of many urban dwellers, the climate is projected to change from known conditions to conditions unlike those experienced in the past by their parents or grandparents (Fitzpatrick and Dunn, 2019). While these changes are of great concerns to many scientists, typical scientific statements such as *"global temperature is expected to rise 1.5^{o}C by 2100"* may be difficult for urban dwellers to understand, but a clear visual interpretation into something more like a personal experience in line with the current needs of urban areas can be the solution to communicating the changes. A proper understanding of these changes provides a guide to most developing cities who yet to formalise concrete climate adaptation plans to avoid the environmental and economic consequences (Fitzpatrick and Dunn, 2019). To improve the understanding of decision makers on urban vulnerabilities to changes in climate conditions, the translation of the scientific forecasts or projections of global climate change into relatable experiences is required to bridge the gap between the climate experiences of the past, current and future.

In the context of the study, climate conditions defined here as average temperature and total precipitation and their impacts on urban centres are used to describe the experiences of climate change by urban dwellers. They are regarded as inter-dependent as changes in any of the variables of climate triggers environmental responses on urban settlement (Wilbanks and Fernandez, 2014). For urban areas; concentration of wealth, infrastructure, productivity, material goods, and people are the major components, but their functional rigidity and complex organisation make them a vulnerable system in a climate that is changing (Wilbanks and Fernandez, 2014). Given the population growth rate of urban areas, the changes in climate poses a serious threat to sustainable urban development, placing many cities at risk thus resulting in escalating human and economic losses. Historically, urban areas have been and are often still perceived as places of refuge from disasters and hazard (Wilbanks and Fernandez, 2014). But despite many uncertainties concerning the magnitude and frequency of hazards, and their specific impacts, climate change will inevitably increase the susceptibility of urban societies if no effective adaptation takes place (UNHABITAT, 2011). Based on the scientific consensuses and growing climatic concerns, most cities will have to implement climate adaptation plans geared at addressing these issues. Although, the gap in addressing these issues is often associated with a lack of understanding from major decision makers. Developing a realistic way to convey climate change information and future projections in a relatable manner will enhance the understanding. Climate analogy bridges this gap by providing relatable illustration of the changes, raise awareness, and investigates the shifts and appearance of new climates (Beniston, 2014).

In the context of urban area development, temperature and precipitation are two dimensions of climate change measured to show a correlation between climate change and urbanization on the African continent (Yoro and Daramola, 2020). In Europe, Asia and American, recent and continuous warming as a result of highest anthropogenic emissions of greenhouse gases ever recorded has had impacts on human and natural systems especially in urban centres (Yoro and Daramola, 2020). Annual global temperature is likely to be at least 1°C warmer than preindustrial levels (defined as the 1850-1900 average) in each of the coming five years and is very likely to be within the range 0.91 – 1.59°C (Young and Young, 2021). Surface temperature has increased by 0.5°C or more during the last 50 to 100 years over most urban areas in Germany, Poland and the United Kingdom (Hibbard *et al.*, 2007; Nicholson, 2013), while regional increase in maximum temperature is expected leading to intense and longer heat waves (Seneviratne *et al.,* 2016; Stott, 2016).

Evidence of the changes in precipitation attributed to urban area development indicates alterations of local climatic conditions, changes in intensity and duration which has led to significant environmental impacts. A study of 200 European cities showed that 72 percent of these cities do not have climate adaptation plans (Reckien *et al.,* 2014). A realistic way to convey climate change information and future projections in a relatable manner will be to enhance the understanding of the decision makers through the climate analogue approach. In areas like the United Kingdom where mean precipitation are projected to decrease, the intensity is projected to increase and with longer periods between rainfall events (Hibbard *et al.*, 2007).

In West Africa, mean precipitation is projected to increase and urban dwellers may experience increases in precipitation intensity and duration but there would be longer periods between rainfall events (Hibbard *et al.,* 2007; Moss *et al.,* 2010). Altogether, these changes in the climatic conditions may threaten the sustainability of urban development while placing many cities at risk. But despite these scientific consensuses and growing climatic concerns, most cities are yet to implement climate adaptation plans geared to address these issues. This gap is often associated with a lack of understanding from both civil society and decision makers.

Although, some major cities in Nigeria are faced with environmental problems arising from changes in precipitation, the challenges are as a result of unplanned and hasty urbanization process (Mohammed *et al.,* 2014). Proper studies on urban climatic management have become imperative, particularly in rapidly growing cities seeking to mitigate climate change and achieve sustainable urban development. To provide understanding of the impacts of climate variables on urban areas, an in-depth knowledge on the city-disasters nexus is crucial, allowing city authorities and planners to mainstream adaptation; that is: to modify their work so as to act upon increasing risk and, ultimately, achieve disaster-resilient cities. Achieving these requires knowledge of future changes through climate projections. The current generation of models indicates that precipitation generally increases in the areas of regional tropical precipitation maxima while intensity of precipitation events is projected to increase particularly in the global South.

The climate analogues approach involves examining the climate of a location relative to the climate of another place with a statistical technique that quantifies their similarities. (Beniston, 2014) described how climate analogy can be used to provide illustration of the changes in climate, awareness raising, ecological research and investigation of shifts and appearance of new climates in the climate change context. Studies have shown the use of the approach in climate change management (Fitzpatrick and Dunn, 2019). The potentials of the climate analogy approach in urban context are yet to be harnessed in Nigeria and Africa at large. Identifying Nigerian cities tomorrow's climate in the present day could provide the adaptation solutions to the challenges of climate change. Investigations on how climate analogues can help inform strategies for effective climate change adaptation and clear visualization of the potential impact are on-going (Sheppard, 2012). Therefore, there is a significant need to develop innovative methods of providing intuitively comprehensible climate information which is presented in line with the current needs of urban cities in view to improving the adaptation to the future impacts of climate change including extremes in temperature and precipitation.

1.2 Statement of the Research Problem

The nature and magnitude of the spatial and population explosion in most Nigerian cities has exposed the failure of existing development frameworks to adopt climate resilience strategies. This has created a very complex scenario for urban planning and administration in the context of pressing climate change concerns. Changing precipitation and higher temperatures have led to a high rate of evaporation and urban thermal discomfort leading to an increase in the occurrence of severe weather events (drought, heatwaves and infrastructural loss from flooding) (Scruggs and Benegal, 2012a). The vulnerability to climate change and variability is high in these cities, and it is even further aggravated by their low adaptive capacity. The disconnect between the potential threats of climate change and societal action arising from these multiple factors is a major problem given how people perceive and conceptualize climate change.

The Translation and communication of climate impacts in terms of personal experiences may help overcome some of the barriers to public recognition of the risks of climate change. With so many uncertainties about the future impacts, a simplified understanding of the impacts could be the key to raising public awareness and increasing the knowledge of the expected changes (Araos *et al.,* 2016). The lack of understanding in the connection between potential threats of climate change and future implications on urban areas is of great concern. For example, rapid urbanization without efforts to increase resilience will expose cities around the globe to enormous risks (Scruggs and Benegal, 2012a). Consequently, with an attended impact on cities' basic services, infrastructure, human livelihoods and health, it is essential, to make cities an integral part of the solution in fighting climate change. For most parts of the globe, increase in extreme climatic events especially with respect to heat and cold waves in recent years have been a major impact on urban dweller (Christidis *et al.,* 2015; Matthews *et al.,* 2017). Within the tropic like Nigeria, heatwaves have been found to cover most parts of the Country nearly every year, causing high mortality, and affecting a large percentage of the urban population (Smith *et al.,* 2020). An investigations of climate variables focusing on future conditions and their interpretations into historical relatable experiences are essential to improving the understanding of potential threats and possible planning opportunities.

The current climate events observed in most West African cities are perceived to be more dangerous because of the geographical position in the Tropics and the general vulnerability of the population (Riede *et al.,* 2016). Predictions on possible increase in temperature and precipitation events for the future of West Africa climate have also been projected. Observations have been made about the increase of these climate events in Nigeria, and these may become the usual in the future. Gbode *et al,* (2015) and Abatan *et al,* (2016) indicated a significant increase in the fraction of hot temperature events and a decrease in the fraction of cold in Nigeria, while studies like (Dosio, 2017) and (Russo *et al.,* 2014) provided evidence of increased exposure of urban population to precipitation extremes at both regional and global level especially in the later part of the twenty first century (Gasparrini *et al.,* 2017; Mora *et al.,* 2017). However, a thorough and direct comparisons of the characteristics of future climate extreme conditions and the urban population exposed to them under the different climate scenarios are yet to attract attention especially in West Africa.

Similar to many other African countries, major cities in Nigeria are faced with environmental problems which majorly contributes to emergency risk and changes in climate conditions as a result of unplanned and hasty urbanization process (Mohammed *et al.*, 2014). The primary consequences of these are the consistent changes in the climate conditions of urban atmosphere (Mohammed *et al.*, 2014).

Similarly, in the City of Kano, there was an upward change in microclimate temperature of nearly 2 °C in 2018 compared to 1980 (Mohammed *et al.,* 2014). These changes witnessed in urban form and climate are attributed to rapid urban expansion and poor planning systems (Mohammed *et al.,* 2014). Abuja city in recent times has experienced an increase in both duration and intensity of precipitation. Urban growth in Abuja has increased and extreme stress to the urban dweller has been widely reported. This is particularly true for the city due to massive conversion of natural vegetation and agricultural lands to urban development (Isioye *et al.,* 2020). Similar prolong urban transformation in Lagos due to poor urban governance, poorly maintained critical infrastructure and the coastal location of Lagos city has further compounds climate vulnerability of the city to flooding (Aderogba *et al.,* 2012). These transformational situations in terms of built-up and population density has given rise to the enormous challenges faced by traditional and economic cities in Nigeria and West Africa and their preparedness to cope with local and global climate change (Ehrlich *et al.,* 2018).

Based on scientific and contextual importance is the question of identifying the current climatic conditions of the urban areas in Nigeria; query of where the future or current climate conditions of a city can be found in the historical periods and extracting the possible implications of these changes in climate. Within the current century, the climate of many regions is projected to change from the present to in some cases totally different conditions from climates experienced in the past (Fitzpatrick and Dunn, 2019). An effective way to determine such similar places is to make use of projected climate data under different scenarios through the climate analogue approach. Since climate plays a crucial role in cities, as it influences human comfort and drives energy consumption. Thus, climate-responsive policies and strategies can help cities adapt to climate variations and create more resilient, and sustainable environment. The climate analogues can help communicate what future climate may feel like to urban residents in a broad sense, with the aid of meaningful visualization which in turn helps in raising public awareness of climate change. Approach like this is effective for conveying climate change information (Jylhä *et al.,* 2010). Furthermore, the study seeks to translate climate forecasts in numbers and statistical form into something more likely to a personal experience with present-day climates thus, improve the understanding of the future climate and the potential threats and opportunities (Nicholson, 2013).

Climate investigations focusing on future climates of urban cities similar to the present in West African cities are few, and the use of the climate analog approach for urban climate adaptation has hardly been explored ((Jylhä *et al.,* 2010; Ehrlich *et al.,* 2018; Fitzpatrick and Dunn, 2019; Isioye *et al.*, 2020). Building on previous studies (Hallegatte *et al.,* 2007; Fitzpatrick and Dunn, 2019), an extensive method which focuses on matching climates precisely and reliably was adopted and redeveloped to examining the implications of precipitation and temperature change in the future to the present for some major cities in Nigeria.

To improve on these studies, recent climate conditions in form of extreme events were examined alongside the identification of the future climates in order to provide a better understanding of the impacts of climate change on the cities examined. This research seeks to provide insights into the possibility of using climate analog, both as a decision support and awareness tool for the identification of possible adaptation strategies and provide insights into the future realities of climate change but relatable to the present conditions.

1.2.1 Research Questions

1. What are the trends in annual temperature and precipitation for the cities from 1991 to 2020?
2. Which historical place on the globe shares similar climate with the future of the six selected cities in Nigeria by 2030s and 2050s under the RCP4.5 and RCP8.5 scenarios?

3. Which of these six cities in Nigeria will experience new climates by the 2030s and 2050s?
4. What are the implications of the new climates on each of the selected cities?
5. What are the changes in rainfall and temperature extremes over the cities?

1.3 Aim and Objectives of the Study

The aim of this study is to evaluate the future of urban climates for major cities in Nigeria with a contemporary analogue approach and its implications for the population. The specific objectives are to;

i. Examine the recent trends in temperature and precipitation for the six cities from for the period of 30 years.
ii. Identify historical climates (1971 to 2000) similar to the projected climates of the six cities under the RCP4.5 and RCP8.5 climate scenarios for 2021 to 2050 and 2041 to 2070 periods by dissimilarity analysis.
iii. Identify and classify the cities with new climates by 2020 to 2050 and 2040 to 2070.
iv. Examine the implications of the new climates on each of the selected cities.
v. Evaluate the extremes of precipitation and temperature over the selected cities by using the climate indices.

1.4 Justification for the Study

(a) Policy Improvement: Given the development and coordination of climate adaptation plans for Nigeria, the National Council on Climate Change (NCCC) in Nigeria could adopt the outcomes from this study as a heuristic tool for policy makers to understand the main features of the adaptation. The Federal and State Ministries of urban planning, Federal Ministry of Environment and Ministry of Work would benefit from this study as it can help facilitate effective decision-making in response to both on-going and future impacts through improved policies and directions in developmental paths. The analogues could provide a unique opportunity for urban managers to establish effective response strategies or roadmaps to address the potential future impacts. For the urban areas, the climate analogues analysis seeks to inform institutions responsible on direction of infrastructural development by assessing the analogue sites. For cost benefit assessments, Ministries of Finance and Nation Budget could adopt the outcomes for allocation of funds in panning for adaptation, while it provides guidance to the National Assembly during budgeting vetting and Government agency oversights.

(b) Performance Improvement: The understanding of the future impacts of climate change and relating it to the present is likely to provide some good insights into dealing with the challenges it may pose. While, aiming to make cities and human settlements inclusive, safe, and sustainable especially for a country like Nigeria; "*Climate Action (Goal 13) and Sustainable Cities and Communities (Goal 11)"*, with a larger population residing in urban areas (NpopC, 2006; Binaisa, 2013; Fabiyi and Olubunmi, 2018), there is need for intelligent urban planning that creates safe and resilient cities to inspiring living conditions. The assessment of major city analogues can facilitate the understanding of the future impacts of climate change as well as help city planners to visualize it. It will support the climate change policies well as communicate the uncertainties and magnitude of the future impacts.

(c) Body of Knowledge: The exchange of ideas and concepts for researchers from the analogue sites can help provide opportunities to improve the understanding of local practices and examination of the adaptation options whether they are transferrable to the climate analogue sites. In urban setting, expanding the climate analogue approach by evaluating urban systems at analogue locations may be useful as testing grounds for recommended practices and to test the adaptive capacity of urban areas. Changes in practices and production levels over time in the analogue location may also be used as indicators of the mechanisms adopted to reduce vulnerability and enhance resilience of households. In the agricultural sector, the analogue approach can serve as a possible approach to overcome crop management limitations and model projections. By developing different cropping systems from those at the target site, farmers in the target location may learn lessons for adaptation from practices that are currently being used at the analogue site.

(d) Further Research: By highlighting a need for more studies that target city-to-city interactions to draw lessons, emphasizes must be placed on further research to avoid blanket adaptation strategies without careful considerations of the characteristics of the analogues. More studies are required before adopting comprehensive integrated approaches (via transfer and scale-up of local solutions), multidimensional resilience to address the challenges.

1.5 The Study Area

1.5.1 Geographical Location

Nigeria is located approximately between Latitude: $4^0$15′ and $13^0$55′ North of the equator and Longitude: $2^0$40′ and $14^0$45′ East of the Greenwich meridian, in the western part of Africa (Figure 1). With an estimated land area of 923,000 square kilometres, Nigeria occupies about 14 percent of the land area of West Africa (National Bureau of Statistics, 2019). The country borders with Chad, Chad basin and Cameroon in the east, Benin Republic in the west, and Niger in the north. (Tijani, 2023).

The cities namely; Kano located in Northern Nigeria between 11°50′ N and 12°07′ N and 8°22′ E and 8°47′ E (Mohammed and Musa 2014), Abuja located in the Guinea Savannah between 7°20′ and 9°15′ North and 6°45′ and 7°39′ East (Enoguanbhor *et al.*, 2019), Makurdi located in the Guinea savannah of Nigeria on 7° 43' 58.8" N and 8° 32' 20.76"

E (Iortyom *et al.,* 2022). It is the capital city of Nigeria situated at the centre of the Federal Capital Territory and bordered by Nassarawa, Niger, Kogi, and Kaduna states. Benin located in the humid tropical rainforest belt of Nigeria and lies between 6º23.055' N and 6º27.339´ N and 05º36.0018´ E and 05º44.130´ E (Aikpitanyi *et al.*, 2019). It is situated in Edo State, South-South part of Nigeria and shares borders with Kogi, Delta and Ondo States. Lagos is located in the tropical rainforest zone of Nigeria (Healy *et al.*, 2020); (Aliu *et al.,* 2022) between latitude: 6° 23′ and 6°41′N, and longitude 2°42′ and 3°42′E (Shiru *et al.,* 2020a). It was the former capital of Nigeria and regarded as the economic hub based on the proximity to the Atlantic Ocean and the importation activities. Lagos share borders with Ogun and the Atlantic Ocean. Port Harcourt is an oil rich city situated in Rivers state, South – South region of Nigeria. It is located on Latitude 4°55′N to 6°55′N Longitude 6°55′E to 7°05′E (Okunola *et al.,* 2022). These cities have established populations of well over three million people. Apart from Abuja which is a modern city created in 1990, the other selected cities are traditional and economic cities that have their major evolution from the precolonial, colonial, and post-colonial eras (Fabiyi and Olubunmi, 2018). They represent regional hubs that attract dwellers from both within and outside their geopolitical regions.

Table 1.1: List of the Cities, Population, Area and Population Density

S/n	States	City	Population	Area Km^2	Density(/Km^2)
1	Lagos State	Lagos	12,550,600	3,345	3,752
2	Rivers State	Port Harcourt	7,303,900	11,077	659.4
3	Federal Capital	Abuja	3,564,100	7,315	487.2
4	Edo State	Benin City	4,235,600	17,802	237.9
5	Benue State	Makurdi	5,741,800	34,059	168.6
6	Kano State	Kano	13,076,900	20,131	649.6

Source: (National Bureau of Statistics, 2019)

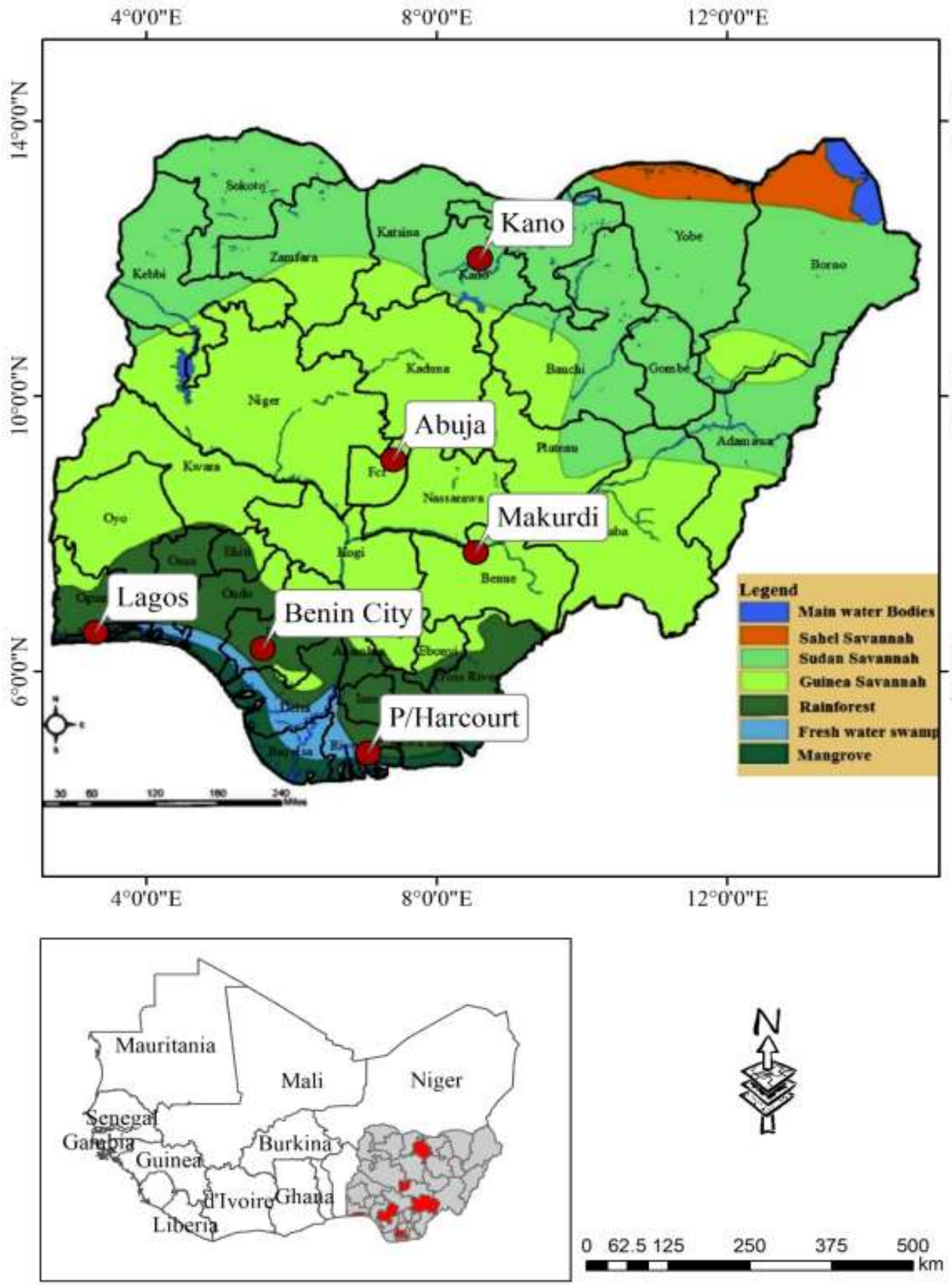

Figure 1.1: West Africa showing Nigeria and the Study Cities.

Source: Author's Analysis of Data (2023)

1.5.2 Climate

The tropical monsoon climate is found in the southern part of Nigeria and it is mainly influenced by the monsoons of the South Atlantic Ocean (Olaniyan *et al.*, 2019). The two main seasons are the dry and rainy seasons with large variations in the climate from north to south. Most of the rainfall occurs between June and September in the semi-arid and arid north, and between April and October in the central and southern parts (Shiru *et al.*, 2020a). Rainfall is usually in high quantity and above the values of 2,000 mm rainfall totals peculiar to the climates of the tropical rainforest (Shiru, *et al.,* 2020a). Regions in the southern part of the country experiences a double rainfall maxima characterized by two peaks periods of high rainfall and long dry season. The tropical savanna climate is extensive in area and covers most of western to central Nigeria and exhibits a well-marked dry and rainy season. The daily maximum temperature during the summer ranges from 30 °C to 37 °C in the south while it goes up to 45 °C in the north (Shiru *et al.,* 2020a). On average, the temperature varies from 20.4 °C in the south-eastern coastal region to more than 28 °C in the north (Shiru, *et al.,* 2020b)**.**

1.5.3 Soil and Vegetation

The six selected cities were drawn from four of the major agro-ecological zones in Nigeria namely; Guinea savannah (Abuja and Makurdi), Sudan savannah (Kano), Rainforest (Benin City) and Mangrove (Lagos and Port Harcourt). Nigeria covers six main agro-ecological zones, the tropical forests (where there is significant tree cover), savanna (insignificant tree cover, with grasses and flowers located between trees), and montane land. The savanna zone is divided into Guinean forest-savanna, made up of plains of tall grass which are interrupted by trees, the most common across the country; Sudan savannah, similar but with shorter grasses and shorter trees; and Sahel savanna patches of grass and sand, found in the northeast Some of the forest zone's most southerly portion, especially around the Niger River and Cross River deltas, is mangrove swamp. Nigeria is ecologically divided into five zones (from north to south) based on the amount of rainfall (Shiru, *et al.,* 2020). The Sahel Savanna is a warm desert climate; Sudan Savanna has a warm semi-arid climate. The tropical savanna climate and Guinea Savanna have a tropical savanna climate whilst rainforest has a mixture of tropical savanna and monsoon climate, and the Mangrove Swamp ecological zone experiences monsoon climate. The mangrove swamps, covering about 10,360 square kilometres and located to the south of the freshwater swamps, are sparsely settled. Strips of sandy beaches and ridges, which vary from a few meters to 16 kilometres, separate the mangrove swamps from the open sea. In addition to natural levees, ox-bow lakes are common landforms in the Niger Delta. The high rainfall in the region, coupled with the abundance of surface water and the flat terrain, create a serious drainage problem and makes construction very difficult. The soils in Nigeria can broadly be categorized into four groups: sandy soils in the Northern zone where the city of Kano is located; lateritic soils in the interior zone which houses the cities of Abuja and Makurdi and the forest soils in the Southern belt that houses Benin city, Lagos and Port Harcourt (Adegbite *et al.*, 2019). Generally, the soils are characterized by loamy sandy and clay with a mixed content of plant mineral composition and easy to farm (Adegbite *et al.,* 2019).

1.5.4 Settlement

Nigeria population is approximately 200 million people with 52 percent of the population in urban areas and about half of the people living in rural areas (*National Bureau of Statistics*, 2019)**.** Densely populated settlements occur along the coast, southwest, and in the Hausa and Kanuri-inhabited areas of the far north (Shiru *et al.*, 2020)**.** The South Western part of Nigeria have long been the most urbanized people in tropical Africa (Aliyu and Amadu, 2017). Their towns, most of them several hundred years old, were originally administrative and trading centres, a function many have retained. About half the region now live in cities, notably Ibadan in Oyo state and Benin city in Edo state. Kano, Zaria, and Katsina are northern towns of the Nigerian Sudan savannah, and are much older owing their existence to the trans-Saharan trade as well as to the agricultural wealth of the surrounding region (Aliyu and Amadu, 2017). Two other study sites, Port Harcourt and Benin City were selected from the Niger Delta region, which is a low-lying region, cut up by a complicated system of natural channels through which the River Niger finds its way to the sea. It is made up of three distinct subregions; freshwater zone, mangrove swamps, and coastal sands.

Abuja is the capital city of Nigeria located in the centre of the country within the Federal Capital Territory. It is a planned city and was built mainly in the 1980s, replacing the country's initial capital city Lagos. At the 2006 census, it had a population of 776,298 (National Bureau of Statistics, 2019) making it one of the ten most populous cities in Nigeria. As of 2015, the city had experienced an annual growth of at least 35 percent, retaining its position as the fastest-growing city on the African continent. Makurdi is the state capital of Benue State which is one of the Middle Belt states in Nigeria. With a population of approximately 4,253,641 in 2006 census (National Bureau of Statistics, 2019), Benue state is inhabited predominantly by the Tiv, Idoma and Igede peoples, who speak Tiv, Idoma, and Igede languages respectively. It is a rich agricultural region with variety in grown crops and major occupation as agriculture. Benue State as it exists today is a surviving legacy of an administrative entity which was carved out of the protectorate of northern Nigeria at the beginning of the twentieth century.

The six cities selected are representatives of the major ecological zones of Nigeria and generally houses a large number of the population of urban settlement in Nigeria which makes them vulnerable to the impacts of climate change.

1.5.5 Relief and Drainage

The elevation of the country is mostly low, with the lowest elevation (0 m above mean sea level) along the Atlantic coast in the south and the highest (2,419 m above) at Chappal Waddi in the northeast (Shiru *et al.,* 2020a). The total length of the coastline of the country is about 850 km. The Udi Plateau, which lies to the east, however attains a height of over 300 meters. This breaks the monotony of the coastal lowlands, which are also characterized by creeks and lagoons on both sides of the Niger Delta (Adegbite *et al.,* 2019). The section which lies in the east of the Niger Delta consists of creeks and swamps which stretch from Opobo town through the Cross-River estuary to the border with the Cameroon (National Bureau of Statistics, 2019).

1.6 Scope and Limitation

1.6.1 Scope

Time Boundary: The study concentrates on assessing climate analogues for major cities of Nigeria in the mid to late twenty first century and the implications on the population. It focuses on two thirty-year periods with the pattern and trends in temperature and precipitation extremes between 1991 and 2020 as base line. For the climate analogue mapping, 1971 to 2000 is used to indicate the historical period climate while 2021 to 2050 and 2041 to 2070 is used to indicate the current and future periods respectively. The periods of study were selected in order to assess the state of climate for these cities in the future in accordance to the projections of the IPPC by the different radiative forcing.

The study was conducted for six major cities in Nigeria namely; Lagos, Kano, Makurdi, Benin, Abuja, Port/Harcourt to achieve proper distribution and comparison. This is due to the fact that each of these cities are representatives of the major ecological zones of Nigeria; Sudan, Guinea, Rain forest, fresh water swamp and Mangrove forest. They also house a large number of the population of urban dwellers, whom are most vulnerable to the impacts of climate change. It is also to achieve proper distribution and comparison. The ensemble means of global climate models of the coupled inter-comparison model project forced by the representative concentration pathways (both Mitigated and unmitigated scenarios) of the Intergovernmental Panel on Climate Change (IPCC) was assessed for the data (IPCC, 2013) due to the global nature and ability to project temperature and precipitation effectively. This study focuses on future impacts of climate based on projections so as to draw insights for sustainable urban planning and adaptation.

1.6.2 Limitations

Some of the limitations of this research includes the accuracy of models to accurately project climate parameters for the study considering the facts that regional climate models cover larger extents and are more of coarse resolution. The availability of historical observational datasets for the six cities were also some of the limitations to the study. To overcome this limitation, a delta method as described in the methodology was applied for the downscaling.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Conceptual Framework

Spatial analogy is conceptualized as a function of space, time and the variables involved in the study. The concept of spatial analogy describes closer locations to be similar as compare to farther locations or that underlying climatic makes spatial inferences appropriate. In researches that involves vulnerability assessment, attributes such as demography and climate are easily used for interpolation and extrapolation of risks in areas of low to none data (Ramírez-Villegas *et al.,* 2011). A typical example is on the mapping of malaria vulnerability in which information from different locations are used for the interpolation of the parameters to be used for its outbreak and transmission over the region (Rogelj *et al.,* 2012). These processes, while rarely labelled as spatial analogues, draw implicitly on analogue conceptualizations, and are used extensively in vulnerability mapping.

In temporal analogue methodologies, present and past information and response to changes in climate factors are used in the understanding of adaptation and vulnerability (Diedhiou *et al.,* 2018). This concept aids the understanding and management of the information gathered on the system from the past climate process and helps in the establishment of potential responses for the future (Ford *et al.,* 2010).The concept of temporal analogue approach is based on the premise that human systems in the near future will probably conduct activities as they have done in the recent past and be influenced by similar conditions and processes, thereby empirically grounding analysis of vulnerability to changing conditions.

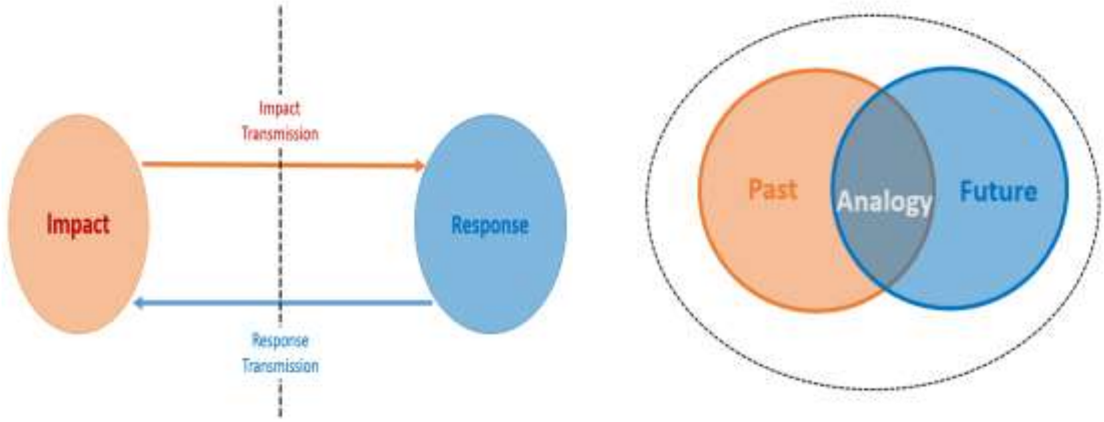

Figure 2.1: Climate Change Cross Borderlines Impact and Response

Sources: Adapted from (Carter *et al.*, 2021)

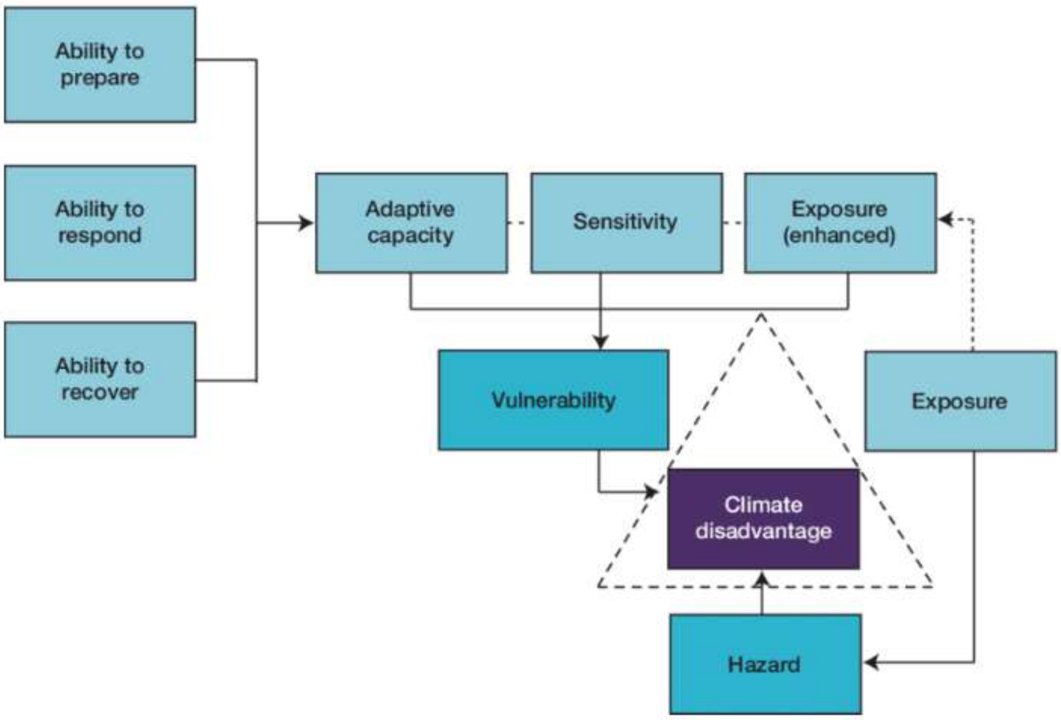

Figure 2.2: Climate Exposure and Vulnerability

Source: Adapted from (Froese *et al.*, 2019) and (Brisley *et al.*, 2012)

2.1.1 Conceptualizing the Climate Analogue Process

Analogy can be defined as ‘The process of reasoning from parallel cases; presumptive reasoning based upon the assumption that if things have some similar attributes, their other attributes will be similar. The methodology of analogues involves the use of information and perception about a particular place or thing (Known) to improve the understanding of another place or thing (unknown) where less is available. This is informed by logical inferences on the basis that two things are alike over time or space in some aspects, then they must be alike in other aspects of forms. Therefore, for the known to provide information on the unknown, they must both share similarities in form and structure. Analogues can be spatial in nature, where information regarding to a problem in a particular location or region are gathered and examined in order to apply the outcomes to another location with similar characteristics. It can also be temporal, where analysis of previous information is used to develop the understanding of the present day and draw out plans about the future (Bastin *et al.,* 2019). These, helps to assess the likelihood and circumstances under which specific outcomes can occur, as well as use what is currently known to make inferences about the future (Schär, 2016).

The climate analogue is a tool that matches the proposed future climate of a location of interest with the current climate experienced in another location using annual average rainfall and maximum temperature. The method is a new way of supporting the results of model outputs and the recommendations of policies (Dunn *et al.,* 2019). In essence, the analogues tool connects sites with statistically similar (‘analogous’) climates across space (in other geographic locations) and/or time (with historical or projected future climates). For example, the analogue site for a place A of interest can be a site far away but with similar climate. (Reckien *et al.,* 2014). Spatial analogue is future climate of a location whose climate today appears very closely to it. This provides opportunity for comparison in terms of planning especially in climate change adaptation. Temporal analogues makes' use of previous datasets thereby providing information on the future and potential impacts of climate, as well as information on adaptation strategies to the anticipated changes from the analogue sites from the past. The method can link targeted fields with the outcomes of models (Rohat *et al.,* 2017). The climate analogues tool identifies areas where either the climate today corresponds to the future climate projected at another location, or the projected future climate corresponds to the current climate of another site. These make use of specified locations, variables such as Minimum and Maximum temperature, precipitation and for the future-related analyses, and one or more climate scenarios as introduced by the IPCC (Bastin *et al.,* 2019). The variables to be used can take various forms of time dimension at any step of the analysis (hourly to yearly).

The application of the analogue method for regional or global search for a particular site requires the use of climate scenarios for the forecasting of the climate of that location. The result would then become the outcome of the comparison between the site's climate and all other climates in all sites of the world using the dissimilarity index (Hallegatte *et al.,* 2007). This comparison is a function of only the specified variable. The measures of dissimilarity can be used in the geographical information system software, statistical packages and can be displayed in grid and tabular forms (Mahony *et al.,* 2017). With the analogue's analysis, outcomes can be generated with high resolution precision for any region of the world. These would depend on data availability; spatial scale and the climate scenarios being considered.

2.1.2 The Potentials of Climate Analogues

Apart from the benefits of the analogue approach being scientifically based, findings of climate analogues studies are thought to be easily understandable, hence can successfully raise awareness of a lay audience about climate change issues (Kopf *et al.*, 2008; Jylhä *et* *al.*, 2010; Beniston, 2014; Rohat *et al.*, 2017). The findings from this study of which would be straightforward and readily comprehensible, can potentially raise awareness of urban dwellers and decision-makers about both the magnitude and the pace of climate change, particularly at city scale. When cities' residents and stakeholders are presented with a graphical representation of the changes in their city's future climate, they may immediately realize what climate change actually means in terms of the changing climatic conditions and what the magnitude of these changes is. As an example, (Rohat *et al.*, 2018) shows that Berlin's climate is shifting throughout Europe to reach North Spain by the end of the twenty-first century. Knowing that the climate in North Spain is much hotter and drier, with more frequent and intense heat waves, residents of Berlin could easily apprehend the magnitude of climate change and immediately envision the type of future climatic conditions they will have to cope with. Furthermore, displaying the different locations of Berlin's future climate at different future time periods might also raise awareness about the pace and dynamics of climate change, emphasizing on the fact that the speed of change is greatly increasing throughout the twenty-first century.

In addition, the approach might also be of great use for decision-makers and urban practitioners in charge of designing and implementing adaptation strategies in urban areas. Indeed, by closely looking at the current climatic conditions of their cities, decision-makers can readily envision the future climate impacts and vulnerabilities that their respective city will face. In the same line, by looking at the adaptation options that are currently implemented in their analogue cities, urban practitioners can immediately and easily identify the ones that would have to be implemented in their own city to be well-adapted to the future climatic conditions. Such use of the climate analogues approach as decision-support tool shows great potential (Rohat *et al.*, 2017) but has remains poorly explored especially in African. On the other hand, certain factors can hinder the exchange of adaptation strategies between cities sharing similar climate at different time periods. For example, two cities of a similar transect might be too different in terms of size, population's characteristics and functionality, to efficiently share their best practice and planned adaptation. Finally, cities are not always well-adapted to their current climate, meaning that their adaptation strategies should not be taken as an example of good practices. In this case, knowledge sharing would only allow identifying future impacts and vulnerabilities.

2.2 Theoretical Framework

2.2.1 Theory of Climate and Time in Analogue Approach

The concept of analogues mainly provides understanding for the relationship between time and climate. It serves as a point of reference for the comparison of the past, present and future while providing information based on the point of reference. A typical example is the use of information about flood that had occurred in the past to provide informed assessment of the possibility of such occurring in another location. This would help inform personal vulnerability and the urgency to act in particular ways. Similarly, information of the impacts of previous climate impacts can be used as a reference in understanding the extent and possible damages that may occur as a result of the climate (whether high or low). Therefore, previous events provide its self as an analogue to current events and can be used as benchmarks to plan for adaptation and increase awareness.

Using the scenarios for the projections for global warming, summers in Illinois would most likely feel like current "summers in Texas or Oklahoma by the end of the century". The heatwave and drought of 1988 provides its self as a benchmark for major drought events both at the present and in the future to come. These type of drought and flood events can serve as experiences and narratives of the potential risk thereby providing a guide for current and future risk perceptions (McNabb and Swenson, (2023). These examples illustrate how experiences and narratives of flood and drought and their outcomes are continuously updated as current events move backwards in time and become historical benchmarks for similar current events.

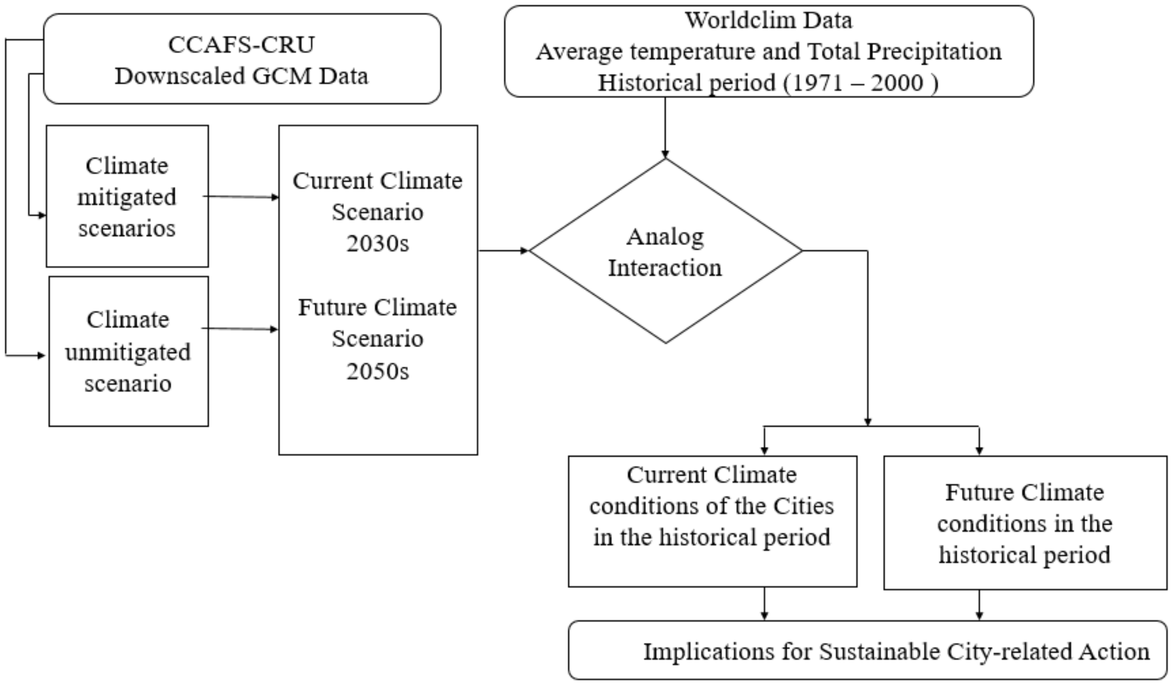

Figure 2.3: Analogue flowchart

Source: Adapted from Asonibare *et al.* (2024)

2.2.2 Anthropogenic Global Warming Theory

The first theory of climate change contends that human emissions of greenhouse gases, principally carbon dioxide (CO_2), methane, and nitrous oxide, are causing a catastrophic rise in global temperatures. The mechanism whereby this happens is called the enhanced greenhouse effect and referred to as the anthropogenic global warming. Energy from the sun travels through space and reaches Earth. Earth's atmosphere is mostly transparent to the incoming sunlight, allowing it to reach the planet's surface where some of it is absorbed and some is reflected back as heat out into the atmosphere. Certain gases in the atmosphere, called "greenhouse gases," absorb the outgoing reflected or internal thermal radiation, resulting in Earth's atmosphere becoming warmer than it otherwise might be. Water vapour is the major greenhouse gas, responsible for about 36 to 90 percent of the greenhouse effect, followed by CO_2 (<1 to 26 percent), methane (4 to 9 percent), and ozone (3 to 7 percent). During the past century, human activities such as burning wood and fossil fuels and cutting down or burning forests are thought to have increased the concentration of CO_2 in the atmosphere by approximately 50 percent. Continued burning of fossil fuels and deforestation could double the amount of CO_2 in the atmosphere during the next 100 years, assuming natural "sinks" don't grow in pace with emissions (Field *et al.,* 2014).

This theory supports and contributes to the continuous evidences being gather by scientist on the increase in the concentration of greenhouse gases in the atmosphere and the need to adequately plan and prepare for the impacts of climate and its associated changes. The analogue approach provides a tool which could provide relatable facts and in turn provide planned adaptation.

2.2.3 The Storylines of Future Climate Scenarios

The storylines of the IPCC scenarios were constructed to explore future developments in the global environment with special reference to the production of greenhouse gases. The scenarios contain various driving forces of climate change, including population growth and socio-economic development. The SRES team defined four narrative storylines; A1, A2, B1 and B2, describing the relationships between the forces driving greenhouse gas emissions and their evolution during the 21st century for large world regions and globally. Each storyline represents different demographic, social, economic, technological, and environmental developments that diverge in increasingly irreversible ways (IPCC, 2013).

1. A1: (Globalization, emphasis on human wealth Globalized and intensive market forces)

The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income (IPCC, 2013).

2. A2: (Regionalization, emphasis on human wealth by regional, intensive clash of civilizations): The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines (IPCC, 2013).

3. B1:(Globalization, emphasis on sustainability and equity): The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic and environmental sustainability, with improved equity, but without additional climate initiatives (IPCC, 2013).

4. B2: (Regionalization, emphasis on sustainability and equity, extensive mixed green bag): The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with

continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels (IPCC, 2013).

2.2.4 Representative Concentration Pathways (RCPs)

A Representative Concentration Pathway (RCP) is a greenhouse gas concentration (not emissions) trajectory adopted by the IPCC. The RCPs are consistent with a wide range of possible changes in future anthropogenic GHG emissions, and aim to represent their atmospheric concentrations (IPCC, 2013).

Table 2.1: Scenarios based on Climate Forcing and their Characteristics

S/n	Name	Radiative forcing	Concentration	Pathway
1	RCP8.5	>8.5 W/m^2 in 2100	> ~1370 CO_2-eq in 2100	Rising
2	RCP6	~6 W/ m^2 at stabilization after 2100	~850 CO_2-eq (at stabilization after 2100)	Stabilization without overshoot
3	RCP4.5	~4.5 W/ m^2 at stabilization after 2100	~650 CO_2-eq (at stabilization after 2100)	Stabilization without overshoot
4	RCP3-PD[3]	~3W/ m^2 before 2100 and then decline	~490 CO_2-eq before 2100 and then decline	Peak and decline

Source: (IPCC, 2013)

The Coupled Model Inter-comparison Project Phase 5 (CMIP5) is a collaborative framework designed to improve knowledge of climate change, being the analogue of Atmospheric Model Inter-comparison Project (AMIP) for global coupled ocean-atmosphere general circulation models (GCMs) (Hawkins *et al.*, 2013; Hibbard *et al.*, 2007). The CMIP5 scenario runs, which provide a range of simulated climate futures (characterizing the next few decades to centuries), can be used as the basis for exploring climate change impacts and policy issues of considerable interest and relevance to society

(Tian and Dong, 2020). CMIP5 provides a framework for coordinated climate change experimentation that over the next several years promises to yield new insights about the climate system and the processes responsible for climate change and variability (Ding *et al.*, 2020; Taylor *et al.*, 2012). For example, the Coordinated Regional Downscaling Experiment (CORDEX), after applying a variety of methods, will produce high-resolution "downscaled" climate data based on the CMIP5 simulations (Romeiras *et al.*, 2014).

2.3 Review of Related studies

2.3.1 Overview of Urban Climates and Analogues

Given the large and ever-increasing number of urban inhabitants globally, and the profound effects of cities and their inhabitants on the atmosphere, both within and beyond urban limits, ever increasing attention has to be directed towards the study of urban climates. Urbanization and the conversion of the Earth's surface to urban uses are among the most visible and rapid anthropogenic changes. In recent years the most explosive population growth has occurred in developing countries (Roth, 2007). Urbanization in these regions has brought about a number of environmental problems at various scales. As cities expand it is becoming increasingly clear that environmental impacts are not just limited to the actual footprint of a place, but may indeed occur at regional and global levels (Romero *et al.*, 2020). Cities produce their own microclimate, but are connected to regional and global climates through the chemistry of the atmospheric effects on radiation balance and greenhouse gas emissions (Emmanuel, 2012).

Past-urban climate research has primarily focused on North American and European cities located in mid latitude climates in the Northern hemisphere (Roth, 2007). In contrast, a similar body of work and therefore understanding in the equatorial or subtropical context is not readily available (Roth, 2007). This is unfortunate because much of the future urban growth will take place in cities located in low latitudes (Roth, 2007). Many of these cities have sprung out from rural towns in very short time, often without much planning or restrictions on land use. They are already experiencing deteriorating environments and are often in a weak position to handle the influx of people and the associated social and environmental problems in a sustainable way. Climate-related environmental problems in (large) tropical urban agglomerations include; water related issues such as flooding and drought and high levels of heat stress. Many of the cities in developing countries lack adequate knowledge, technological and scientific means to effectively research and mitigate these problems, mainly due to other pressing issues of daily survival (Roth, 2007).

2.3.2 Urban Areas and Climatic Analogues

Veloz *et al.* (2012) examined Wisconsin for climate analogues in the 21st-century by calculating the climatic dissimilarity between the future climate as projected for each Wisconsin grid cell and all grid cells from the observational dataset of late 20th-century using the standardized Euclidean distance (SED) as the measure of climatic dissimilarity. The authors used different global climate models downscaled at a high resolution of 0.1 decimal degree for the state of Wisconsin. Observations from gridded data were used for end of 20th Century 1950-1999 to describe the late-the climates of Wisconsin with a monthly time resolution and historical climate record of 187 to 2008. Eight different variables for climate were used in the calculation of the analogue analysis based on the projections of the 4th assessment report of the Inter- Governmental Panel on Climate Change for Future climates for Wisconsin in the United State of America. The projections consider the B1, A1B, and A2, which represents various future scenarios for economic development as well as the concentration of the greenhouse gases in the atmosphere (IPCC, 2013)**.**

The study examined temperature and precipitation on different scales; monthly, seasonally and yearly. For the monthly and yearly analysis, temperature and precipitation were calculated separately for each month and year respectively. For the seasonal analysis, temperature and precipitation were also calculated for the following seasons; September–November, March–May, December–February and June–August and the summary of their statistics reported. The analysis employed was the standardized Euclidean distance which is a measure of dissimilarity in climatic parameter. This makes use of a comparison method for the climate variable of the present city been examined and the future climate of the world as projected by the scenarios and model combination. A major gap in the study may be as a result of the non-inclusion of multi-model ensemble in the assessment of the characteristics of the future climate of Wisconsin.

The results indicated that Wisconsin's future climate at the end of the late twenty first century will differ substantially unless the projected CO_2 emissions are countered or mitigated. From the analysis of the analogues, the closest contemporary climate similar to Wisconsin for the end-21st-century projections is not found within the state and located hundreds of kilometres away. Thus, references to be used in the preparation of plans and strategies to combat the impacts of climate change in the city would have to be sort from beyond the boundaries of the state.

2.3.3 Urban Areas' Climate Shift and the Characterization

Rohat *et al.* (2018) characterized European cities' climate shift in an exploratory study based on climate analogues. They described climate matching approach as a method to match one climate with another. The method is based on the CCAFS index (Climate Change, Agriculture and Food Security similarity index and aggregation of various climate statistics (Ramírez Villegas *et al.*, 2011)**.** It is based on a set of arbitrarily established thresholds and comparison between a set of univariate climatic criteria (Rohat *et al.,* 2017; Veloz *et al.,* 2012) or indexes based on the standardized Euclidean distances (SEDs) (Veloz *et al.,* 2012) which allows for ease of control in the climate analogues' in terms of climatic proximity. The use of a similarity index allows for the identification of the climatically closest one analogue and their respective ranking.

The authors of the study used monthly mean precipitation and monthly mean temperature as the climatic variable for the analysis. The variable was categorized into climatological seasons to represent winter and summer month respectively (December to January, June to August). They also indicate months with minimum and maximum temperature as well as cold and warm spells.

The set of data used for all the analysis were derived from the European project ensembles of (2009). To reduce the uncertainties associated with the use of a single regional climate model (RCM), they computed multi-model means of the five climatic variables. The five climatic variables were computed monthly and annually for the five 30-year periods and for all the grid. To identify the climate analogues of a given location of interest and time period, they first computed and averaged (as per grid points in the computational domain) the Euclidean distances between the location of interest current climate and the future climate of all the grid points, for the five climatic variables. They computed their similarity index based on an unweighted SED metric and ranked them to identify the best one, in terms of climatic proximity.

The results showed that as based on the projections of the special emission report, it is possible to identify and rank climate analogues of any cities and also assess the velocity of their climate shift, for any future time periods. The authors also showed that the climate of the European cities will experience a southward shift in the future based of the spatial analysis of these climate-matching. This would have a direct implication on the urban settlement thereby creating a need for adaptation to the potential future impacts of the changing climate which may also be entirely new to the region

2.4 Examples from Other Regions

The analogue approach has provided an intuitive means of raising public awareness of the implications of climate change for 250 million urban residents of America (Dunn *et al.,* 2019; Fitzpatrick and Dunn, 2019), as well as shown how summer climate could feel by the end of the century (Matthews *et al.,* 2017; Swain *et al.,* 2020). For ecological research, particularly to investigate the shift of eco-communities in a climate change context, one of the most comprehensive application of climate analogue was led by the Research Program on Climate Change, Agriculture and Food Security CCAFS (Ramírez-Villegas *et al.,* 2011) for climate adaptation to agriculture in Africa and South-America. Below are some examples of climate analogues from other continents and Africa.

2.4.1 Analogues for Europe

In an exploratory study, Rohat *et al.* (2017) used 90 different European cities to examine the pattern of the climate change of European cities from 1951 to 2100. Data sets for the case study were from the European project ENSEMBLES of 2009. This provides data using A1B scenario of SRES of the IPCC to generate daily values at 25km horizontal grid-spacing. European cities' climate was found to strictly move towards the south when analysed using the climate analogue approach in the future. The climate shift appears to follow particular north-to-south transects while the direction was specifically determined to move towards the equator. The shifts in the climate will have direct implications for the urban settlement, whom will have to adapt to various impacts to be expected. This rapid changes in the climate will create new issues which were not commonly found in the city climate. The analogue approach was therefore useful in creating awareness in the urban areas about the magnitude of the future impacts of climate change. The awareness is based on the fact that the analogue of their city would have a similar climate to their current city's climate and these changes are expected to be doubled by end of the late twenty-first century as well as located southwards towards the equator.

The approaches provide avenue for proper planning and immediate envision of what the future may hold in terms of changes in climatic condition and at what pace these changes will occur. Furthermore, (Rohat *et al.*, 2017) described the approach as a decision-support tool which would tend to improve the understanding of the risks and impacts of the future climate by learning form their analogues. It also provides for adequate adaptation options, best practices and policies. Exchange of concepts and knowledge between the cities would also with practical applications of climate analogues used for strengthening collaboration between cities and enhance improving the climate and other environmental benefits.

2.4.2 Analogues for America

Fitzpatrick and Dunn, (2019) used climate-analogue mapping to characterize and communicate how climate change may impact the lives of a large portion of the populations of the United States and Canada (western hemisphere north of the equator) for the late twenty first century (2070 to 2099). Five hundred and fifty urban areas were analysed in the study with approximately 250 million inhabitants, including over 75 percent of the population of the United States and over 50 percent of the population of Canada. The climate of these urban areas were examined using minimum and maximum temperature and total precipitation in four climatological seasons. For 2080's climate, (Fitzpatrick and Dunn, 2019) selected two Representative Concentration Pathways, unmitigated emissions (RCP8.5) and a mitigation scenario (RCP4.5) and 27 different earth system models

They found that if emissions continue to rise throughout the 21st century, climate of North American urban areas will become, on average, most like the contemporary climate of locations 850 km away and mainly to the south, with the distance, direction, and degree of similarity to the best analogue varying by region and assumptions regarding future climate. This means climate of most urban areas will shift considerably and become either more akin to contemporary climates hundreds of kilometres away and mainly to the south. For many urban areas, they found substantial differences between future climate and the best contemporary climatic analogue, underscoring that by the 2080s many cities could experience novel climates with no modern equivalent in the study domain (Fitzpatrick and Dunn, 2019).

2.4.3 Analogue for Africa

To illustrate the climate analogue mapping, (Ramírez-Villegas *et al.*, 2011) in a case study described the application of the climate analogue to search for similar climate for Lawra-Jirapa, Ghana (LJG), with the focus on South Asia. Average temperature and diurnal temperature ranges, rainfall and 19 other bioclimatic data sets were downscaled and used for the analogue process. The search was for present and future (2030s) based on the IPCC fourth assessment scenario and 24 different global climate models. They assumed a growing season of April to October for the monthly analyses. The dissimilarity analysis carried out for the temperature (weighted by DTR), rainfall, and the 19 bioclimatic variables utilized 0.5-degree pixel for LJG.

For temperature alone, the search indicated that the closest in terms of climate analogues were located in some humid areas of central Africa, towards south West Africa, and in the low elevations of southern India, where the seasonal temperature patterns matched those of LJG. For the precipitation variable alone, the search indicated that the closest in terms of climate analogues to LJG are areas located around the region but extending towards the Sahel; and in very small pockets of East and central Africa and southwestern India, this measure showed that the most similar sites surrounded LJG, expanding towards southern West Africa and eastern Africa (Ramírez-Villegas *et al.,* 2011).

2.4.4 Added value in Climate Analogue

The analogue methodology can be useful in urban climate understanding in the following ways:

1. Facilitating exchange of knowledge. This involves the identification and connection of analogous sites which would in turn inform better research for the improvement of urban area.
2. Testing new technologies and the validation of computational models. The analogues tool, can help in linking models output with relatable facts on the ground. This allows for better understand of specific urban climate systems and conditions.
3. Learning from history. These involves the use of case studies to improve in the analogue process to improve understanding of climate conditions (Kopf *et al.,* 2008). These case studies can then be analysed for lessons learned, thus building understanding.

2.5 Overview and Key Issues of the Study

Scientific evidences and the gaps gathered over the years suggests the fast changes in climatic condition and possibilities of increased consequences (Moss *et al.,* 2010). The continuous changes have been projected to have far reaching impacts on regions regarded as loser while it would benefit some other region who are considered as the winners of the changes (Roudier *et al.,* 2011). For those regarded as the winners of the changes to climate, the climate system may be further stretched to obtain additional benefits but the opposite would be the case for those regarded as the losers and accelerated adaptation may be resulted to. This is due to the fact that mechanisms used in the past may not be sufficient any long and as such regarded as obsolete. To further benefit from these opportunities, research based approached may be utilized in order to improve and better understand the projections and the potential adaptations. The behaviour of society and institution may be a major reason for the research gaps in the use of the climate analogue. In political and development realms, the plans and policies required in climate change adaptation are based on the outputs of region and global climate model. There still exit a number of unknowns in the use of modelling for the projection of climate and the expected changes due to the complex nature of the earth system and its associated components and as such cannot be fully relied (Challinor and Wheeler, 2008). This implies that model validation for the climate and its components can only be achieved only when the actual year of project comes (Challinor and Wheeler, 2008).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of Materials

This sub section describes the materials and data sets used in the analysis of trends in historical, current and projected climate data of the urban areas and the identification of their climate analogues.

3.1.1 Climate Data

Urban area boundaries shape file was derived from the World Urban Areas dataset.

Table 3.1 shows the cities and their geographical coordinates while the climate dataset includes;

1. Station Data for climate extremes
2. Estimates of historical inter-annual climatic variability (ICV) for each urban area as the baseline.
3. Projections of future climate variables (Precipitation and Temperature).
4. Downscaled and bias-corrected projections of future climate for the 21st century (30-year means of the periods 2021 to 2050 representing the 2030s climate and 2041 to 2070 representing the 2050s. These represents current climate and future climate (mid twenty first century).

Table 3.1: List of the Cities and their Geographical Coordinates

S/n	States	City	Latitude	Longitude
1	Lagos State	Lagos	6.5056	3.4438
2	Rivers State	Port Harcourt	4.8400	7.0217
3	Federal Capital	Abuja	9.0636	7.4284
4	Edo State	Benin City	6.3325	5.6305
5	Benue State	Makurdi	7.7321	8.5390
6	Kano State	Kano	12.002	8.6328

Source: Author's Analysis of Data (2023)

3.2 Methods of Data Collection

To achieve the objectives of the study, the datasets required are two climatic parameters namely; temperature and precipitation (monthly means temperature and total precipitation). For the future climatic parameters, downscaled and bias-corrected projections (Mahony *et al.*, 2017) of future climate (30-year running mean of the period 2021–2050 and 2041 to 2070) which represents a 30-year period at 5min resolution was obtained from the International Agricultural Research Program on Climate Change, Agriculture and Food Security (http://www.ccafs-climate.org/) (Ramírez-Villegas *et al.*, 2011). The dataset comprises of 27 different earth system models' (ESM) of the CIMP5 forced by the representative concentration pathways (RCPs). For this study, RCP4.5 (a mitigation emissions scenario) and RCP8.5 (an unmitigated emission scenario) were employed for the 2030s and the 2050s period for 3 GCMs in the CIMP 5. The datasets were developed as part of the Intergovernmental Panel on Climate Change (IPCC) via the Fifth Assessment Report (AR5) (van Vuuren *et al.*, 2011).

In total, the data set comprise of outputs from 6 future climate scenarios (3 ESMs multiplied by the two (2); RCP4.5 (a mitigation emissions scenario) and RCP8.5 (an unmitigated emission scenario)). For contemporary climatic normal, total monthly precipitation and temperature variables representative of the period 1971–2000 were used. The complementary datasets were obtained from the WorldClim dataset at 5 arc-minute resolution (Hijmans *et al.,* 2005; Fick and Hijmans, 2017). For climatic trends in cities, reanalysis data of NASA power for the six cities were utilized. The 6 cities were selected based on population size, representation from the different agro-climatic zones, geo-political zones and data availability.

3.2.1 Historical data

For the historical climate data, monthly average for temperature and total amount for precipitation were used for the periods of 1971 to 2000 and obtained from the WorldClim portal (https://www.worldclim.org/). WorldClim is a database of global climate data widely used for spatial climate modelling and mapping (Fick and Hijmans, 2017). It is a spatially interpolated monthly climate data for global land areas with a resolution of 5 minutes.

Climate in this study is describe as a combination of temperature and precipitation. The total precipitation was employed to account for intra variability within the season while average temperature accounts for minimum and maximum temperature changes within the period.

3.2.2 Future Data (Climate Projections)

The CCAFS projected dataset was developed by applying the delta method: a downscaling method for the climate model (Navarro-Racines *et al.,* 2020). The pre-processed data based on the analysis method has already been shown as robust in correcting mean climate conditions in different regions (Hawkins *et al.*, 2013). The suitability and wide usage of the data informed the adoption of the study. The delta method was applied to three Global Climate Models from the Coupled Model Inter-comparison Project Phase 5 (CMIP5); CSIRO-Mk3, MIROC-ESM, and HadGEM2

(Navarro-Racines *et al.,* 2020). The outputs were from two representative concentration pathways (RCPs); RCP4.5 (mitigated), a stabilization scenario, where policies are put in place for the reduction of greenhouse gas emission (Lamb *et al.*, 2022) and RCP8.5, an unmitigated scenario, where greenhouse gases continue to rise (Arnab *et al.,* 2021).

3.2.3 Coupled Model inter-comparison Project 5 Data sets (CMIP5)

To assess the data used for the future and current climate, the CCAFS data portal was used to obtain the biased corrected temperature and precipitation. The Climate Change, Agriculture, and Food Security CCAFS-Climate data portal provides global and regional future high-resolution climate datasets that serve as a basis for assessing the climate change impacts and adaptation in a variety of fields including biodiversity, agricultural and livestock production, and ecosystem services and hydrology. The data distributed here are in ARC GRID, and ARC ASCII format, in decimal degrees and datum WGS84. Projections of climate change are available at coarse scales (70–400km).

The data set include monthly maximum and minimum temperatures and monthly total precipitation, and a set of bioclimatic indices, and can be used for assessing impacts of climate change on agriculture and biodiversity. The data are publicly available in the in the CCAFS-Climate data portal (http://ccafs-climate.org). The database has been used up to date in more than 350 studies of ecosystem and agricultural impact assessment. Downscaling techniques range from smoothing and interpolation of GCM anomalies (Tierney *et al.,* 2020; Weli *et al.,* 2017), to statistical modelling (Assessment, 2009; Wang *et al.,* 2016). They differ in accuracy, output resolution, computational requirements and climatic science robustness.

3.2.5 Daily NASA Reanalysis Data

Daily values of precipitation, and minimum and maximum temperature from 1990 to 2020 were retrieved from the archives of the National Aeronautics and Space Administration (NASA). The data accessed were for the six selected urban areas representing the climatic zones of Nigeria (Retrieved on the 3rd of March, 2021). Meteorological parameters are derived from NASA's MERRA-2 assimilation model and GEOS 5.12.4 FP-IT. MERRA-2 is a version of NASA's Goddard Earth Observing System (GEOS) Data Assimilation System (White *et al.,* 2008; Bai *et al.,* 2010; Negm *et al.,* 2017; Ndiaye *et al.,* 2020). It is the first long-term global reanalysis to assimilate space-based observations of aerosols and represent their interactions with other physical processes in the climate system. The horizontal resolution of the primary solar data source is a global 1° x 1° latitude/longitude grid while the meteorological data sources are ½° x ⅝° latitude/ longitude grid. Data validation by (Bai *et al.*, 2010) reveals a better skill on both seasonal and annual scales over West Africa when compared with Global Coordinate Points (GCPs) and therefore recommends NASA data for climate impacts studies

3.2.6 Climate Research Unit Gridded dataset (CRU TS4. 04)

The CRU TS dataset was used to assess the recent trend in temperature and precipitation of the cities. It provides a high-resolution monthly grid land bases observation going back to 1901 and consist of ten observed and derives variables. CRU TS (Climatic Research Unit gridded Time Series) is a widely used climate dataset on a 0.5° latitude by 0.5° longitude grid over all land domains of the world except Antarctica. It is derived by the interpolation of monthly climate anomalies from extensive networks of weather station observations (García-Cueto *et al.*, 2019, 2019; Scruggs and Benegal, 2012b). It was used in this study as the baseline data for the historical period. The CRU TS4.04 variables extracted for the study are; precipitation, daily mean temperature, monthly average daily maximum and minimum temperature for the periods of 1971 to 2000.

3.2.7 Worldclim Data Set

Dataset of spatially interpolated monthly climate data for global land areas at a very high spatial resolution (approximately 1 km^2). Variables included monthly temperature (minimum, maximum and average), precipitation, and solar radiation, vapour pressure and wind speed, aggregated across a target temporal range of 1970–2000, using data from between 9000 and 60 000 weather stations. Weather station data were interpolated using thin-plate splines with covariates including elevation, distance to the coast and three satellite-derived covariates: maximum and minimum land surface temperature as well as cloud cover, obtained with the MODIS satellite platform. The climate variables retrieved are; Average Temperature and Precipitation at 5 minutes. Compiled monthly average climate data for weather stations from a large number of global, regional, national, and local sources, mostly for the 1970–2000 period. Utilizing satellite-derived data and other co-variables, interpolations of these data were done using the thin-plate smoothing spline algorithm implemented in ANUSPLIN. The data are referred to as the 'WorldClim version v2.1 database and are available for download from http://worldclim.org/.

3.3 Data Analysis

This sub-section describes the various analyses used for the identification of climate, temperature and precipitation analogues and the evaluation of extremes as outlined in the objectives of the study.

3.3.1 Analysis of Trends and Time Series

To examine the trend in temperature and precipitation of the selected cities, temperature and precipitation reanalysis datasets as derived from NASA POWER project and Climate research unite CRU is used for the annual mean for the period of 1991 to 2020. The Mann-Kendall test and Sen's slope estimator was employed for the trend detection. The non-parametric Mann-Kendall test is widely used in detecting trends of variables in meteorology and hydrology fields (X. Wang *et al.*, 2019). The statistic S can be obtained by Equation 3.1.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \tag{3.1}$$

Where n is the length of the sample, x_k and x_j are from k=1, 2, …, n-1 and j= k+1, …, n. If n is bigger than 8, statistic S approximates to normal distribution. The mean of S is 0 and the variance of S can be acquired as follows:

$$\text{var(s)} = \frac{n(n-1)(2n+5)}{18} \tag{3.2}$$

Then the test statistic Z is denoted by the Equation.

$$z = \frac{s-1}{\sqrt{var(s)}}, if\ s > 0$$

$$z = \frac{s+1}{\sqrt{var(s)}}, if\ s < 0$$

$$z = 0, if\ s < 0$$

3.3

If Z>0, it indicates an increasing trend, and vice versa. Given a confidence level α, the sequential data is supposed to experience statistically significant trend if |Z|>Z (1-α/2), where Z (1-α/2) is the corresponding value of P=α/2 following the standard normal distribution.

Besides, the magnitude of a time series trend would be evaluated by a simple non-parametric procedure developed by (Lamb *et al.,* 2022; Ndiaye *et al.,* 2020). The trend is calculated by

$$\beta = Median\left(\frac{x_j - x_i}{j - i}\right), j > i$$

3.4

Where β is Sen's slope estimate. β > 0 indicates upward trend in a time series. Otherwise, the data series presents downward trend during the time period.

3.3.2 Analysis of Climate Analogues

To identify present climates similar to the projected climates forced by RCP8.5 and 4.5 scenarios for each urban area, the extractions of climatic parameters projected for the 2030s and 2050s climate from each of the 3 climate scenarios (3 Earth System Models by 2 RCPs) was carried out and the ensemble mean projection. Figure 3.1 shows the climate analogue flowchart.

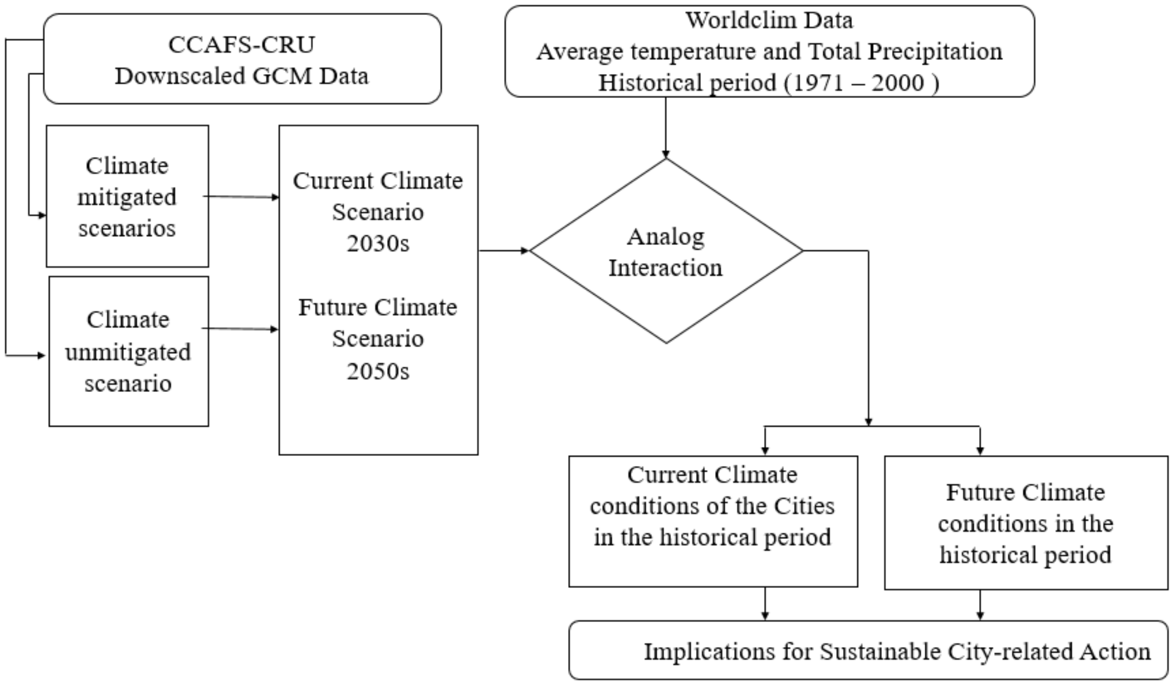

Figure 3. 1: Climate Analogue Flowchart

S**ource**: Author's Analysis of Data (2023)

For the analogue analysis, any location globally in the historical period is matched with other locations in the current and future periods that share similar climatic conditions. To investigate the cities' climate, the analogue approach links the current and future average temperature and precipitation to the historical conditions of another location through a statistical technique that quantifies their similarities. Data from the three earth system models forced by two Representative concentration pathways RCP4.5 (mitigated) and RCP8.5 (unmitigated scenario) were utilised. The model output was averaged for each of the scenarios to form an ensemble in each of the periods considered. In total, the datasets comprise outputs for four future scenarios (two scenarios multiplied by the two periods).

The 'CCAFS dissimilarity' climate analogue method (Ramírez Villegas *et al.,* 2011) which is similar to that described by (Williams *et al.,* 2007) and (Hallegatte *et al.,* 2007) is used to determine the climate analogue for these cities. In the CCAFS dissimilarity measure, future and historical climates are described as vectors of sequential mean values for variable and weight. The dissimilarity is calculated as a weighted Euclidean distance between the variables' vectors for the reference and target scenarios (Ramírez Villegas *et al.,* 2011). The analogues method also accounts for seasonal variations by searching across time steps for the minimum dissimilarity, for example, the rainy season in the global south does not occur at the same time as the global North (Hallegatte *et al.*, 2007)**.** To identify analogues of the cities based on the similarity, Euclidean distances (i.e., dissimilarity indices) were estimated for the current period (2030s averages) and the future period (2050s averages) locations based on their coordinates. The analysis was calculated using the analogues package on R (Ramírez Villegas *et al.*, 2011). Temperature conditions of the cities for each of the current and future scenarios were then paired with its closest historical temperature conditions based on the dissimilarity values. To eliminate unrealistic shifts due to pixel mismatch between the future, current, and historical conditions, the identified place determined to be the best analogue has the highest pixel within the analogue temperature surface. It is important to acknowledge the different limitations of the analogue approach presented above. To estimate the distance of the cities to their respective analogues, the distance tool in ArcGIS was used to analyse the straight-line distance. The climate similarity process includes;

A. Variable Selection

The two climate variables (Temperature and precipitation) were employed to increase the differentiation of climates. This more specific definition of climate is intended to reduce the potential for false analogues without unduly increasing the potential for false novelty. The climate variables are mean temperature and total precipitation.

B. Projections

To conduct assessments of future 21st century projections, an ensemble of 3 CMIP5 model projections is employed. The models chosen represents good performing CMIP5 GCMs over Nigeria as identified by (Shiru, *et al.*, 2020a) and provides the data set for the future analysis. The primary results are based on an "ensemble mean projection" calculated from the anomaly (mean monthly) for each variable in all three models. The results present places that have similar climates to the Abuja, Lagos, Kano, Makurdi, Benin City and Port Harcourt based on the following;

1. Average temperature and Total precipitation
2. Average Temperature only
3. Total Monthly Precipitation

Based on

a) The different RCPs 4.5 and 8.5 represent Mitigated and unmitigated scenarios.
b) Model ensemble of HadGEM3, CSIRO MK3 and MIROC-ESM

C. Scenarios

Future urban climate would be calculated for the RCP4.5 and RCP8.5 scenarios for all the cities in study. The choice of the term emissions scenarios is for simplicity, recognising that these scenarios encompass other major components of radiative forcing. The RCP4.5 and RCP8.5 scenarios represent the future projection as prescribed by IPCC (*IPCC*, 2013).

D. **Calculations**

To determine climate analogues, the 'CCAFS dissimilarity' method, which is similar to that described by (Hallegatte *et al.,* 2007; Williams *et al.*, 2007) 'Hallegatte dissimilarity' was employed. It can be used for any variable for which data are available for several time steps (often days or months, although this can be reduced to a particular season of interest).

In the CCAFS dissimilarity measure, future and present climates are described as vectors of m sequential mean values for v variables (V) and v weights (W). Dissimilarity is then calculated as a weighted Euclidean distance between the variables' vectors for the reference (f) and target (p) scenarios. In Equation 3.5, each variable difference is weighted (i.e. multiplied) with its corresponding weight to account for the different units used. The weight can also be used to alter, or better reflect, the relative importance of the variable in the dissimilarity value:

$$CCAFS = (\sum_{i=1}^{m}\sum_{j=1}^{v} W_{ij} \,.\, (V_{ijf} - V_{ijp})^{z})^{1/z}$$

3.5

Where, z is a parameter that, when equal to 2, produces Euclidean distances, and can be changed to perform sensitivity analyses. A weight can be either a single number or the rate of change in another climate variable (X) with the same time step (m). In that case, the weight is defined as the reference value for that variable (X), divided by its respective target value (Equation 3.6):

$$W_{ij} = \frac{X_{ijf}}{X_{ijp}}$$

3.6

Seasonal variations do not occur concurrently in different locations (e.g. the rainy season in southern Africa does not occur at the same time as it does in the Mediterranean (Hallegatte *et al.*, 2007). The analogues tool can account for this by searching across all m time steps for the minimum dissimilarity, using a time lag (lag, Equation 3.7):

$$CCAFS = \min_{0 \le log \le m-1} (CCAFS_{i=1\ldots m})$$

3.7

By replacing Equations 1 and 2 with Equation 3, CCAFS dissimilarity calculation is given by (Equation 3.8):

$$CCAFS = \min_{o \le lag \le 1} (\sum_{t=1}^{12} \frac{DTR_{if}}{DTR_{ip}} . (T_{if} - T_{ip})^{z} + 1. (P_{if} - P_{ip})^{z})^{1/2}$$

3.8

The higher the value, the more dissimilar the two sites are for that particular pair of climate scenarios. In other words, the lowest value represents the best climate analogue. Based on the dissimilarity analysis two types of data can be loaded into R; gridded data (raster objects, from the package raster), and matrices (built-in objects in R). These data can be loaded for any variable (V), any weight (W), with any time step (m), and for any combination of climate scenarios.

3.3.3 Climate Analogues and Classification of New Urban Climate

To identify and classify the cities with new urban climates by 2021 to 2050 and 2041 to 2060.

Future climate for the six urban areas for the projected 21st century without analogues is regarded as new urban climate. The measure of novelty is the dissimilarity between the projected 21st-century climate of a location of interest and its best analogue among the observed climates. Categorisation based on the Euclidean distance of 0 to 1 gives the classification of the percentage of novelty. As a statistical measure of the departure from historical variability, dissimilarity provides an intrinsically meaningful metric of the general significance of climatic dissimilarities. A measure of dissimilarity between the future climate of the cities in consideration in the 21st century and any other climate at present would provide information on new or disappearing climate. Similarity score = 1 indicates a perfect match, > 0.5 denotes an increasing level, < 0.5 denotes a decreasing level and 0 indicates no similarity

3.3.4 Climate Indices

To assess the current climatic conditions of the cities, the methodology applied estimated the extreme meteorological events with the RclimDex package version 1.3 software and R statistical data analysis. The package is designed to provide a user friendly interface to compute indices of climate extremes. It computes all 27 core indices recommended by the Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI) as well as some other temperature and precipitation indices with user defined thresholds. ClimDex guides a user through an organize data analysis process:

1. **Quality Control:** The first step in the analysis process consists of the application of routine quality control procedures to a user's station data. The quality control checks performed are:

a) Minimum Temperature > Maximum Temperature

b) Precipitation (PREC) < 0.0 mm

c) Identifying outliner values > or < a specified number of standard deviations.

2. **Homogeneity Testing:** ClimDex provides users with a way to detect maximum and minimum temperatures homogeneities. These values can be thought of as discontinuities or shifts in the data record or time series of maximum or minimum temperature.

3. **Calculation of Indices:** Indices of temperature and precipitation in 1991 to 2020 compared to 1961 to 1990 period were calculated using the RClimDex package. To achieve this objective, 12 indices representing extremes of temperature and precipitation from 1991 to 2020 over these six states were calculated. Table 3.2 and 3.3 shows a list of the indices and their definitions as recommended by WMO Expert Team on Climate Change Detection and Indices (ETCCDI) (Donat *et al.*, 2013).

Table 3.2: Temperature indices

Temperature Indices	Indicator	Unit	Definition
Warm Days	TX90p	Days	Percentage of days when TX > 90th percentile
Warm Nights	TX90p	Days	Percentage of days when TN > 90th percentile
Cold days	TX10p	Days	Percentage of days when TX < 10th percentile
Cold Nights	TN10p	Days	Percentage of days when TN < 10th percentile
Warm Spell Duration Index	WSDI	Days	Annual count of days with at least 6 consecutive days when TX > 90th percentile
Cold Spell Duration index	CSDI	Days	Annual count of days with at least 6 consecutive days when TN < 10th percentile

Source: Expert Team Climate Change Detection and Indices (ETCCDI) (Donat *et al.*, 2013)

Table 3.3: Precipitation indices

Precipitation Indices	Indicator	Unit	Definition
Simple Daily Rainfall intensity	SDII	mm/day	Simple precipitation intensity index
Days with ≥ 20mm of rain	R20mm	mm	Annual count of days when PRCP≥ 20mm
Consecutive Dry Days	CDD	Days	Maximum length of dry spell, maximum number of consecutive days with RR < 1mm
Consecutive wet Days	CWD	Days	Maximum length of wet spell, maximum number of consecutive days with RR ≥ 1mm
Rainfall on Extremely Wet Days	R99p TOT	mm	Annual total PRCP when RR > 99p
Total Precipitation	PRCPTOT	mm	Annual total precipitation from days ≥ 1 mm

Source: Expert Team Climate Change Detection and Indices (ETCCDI) (Donat *et al.,* 2013)

3.3.5 R packages for Data Analysis

R is a flexible software package that allows the integration of new features without necessarily modifying the core functions of the software itself (Ramírez Villegas *et al.*, 2011). This functionality is provided by means of packages or libraries, which are built using a basic template. R packages can incorporate new methods and functions, and even introduce new concepts (https://cran.r-project.org/package=climdex.pcic). A package often consists of two main components: scripts and documentation. Scripts are R code files that contain the instructions and commands to be executed, whereas documentation provides detailed information on what variables, arguments, and specific details need to be known when using the functions in the script files. An R package can 'export' one or many functions and, for each exported function, documentation must necessarily exist. Hence, users can see and use all exported functions or methods, whereas all the other nonexported features are, by default, running in the background. All Analysis were performed within the R environment.

3.4 Method of Data Presentation

The analysed data were presented using maps, tables, graphs and narrations. Graphs, charts, and maps provide a visual representation of data, making complex information easier to understand at a glance. Visualisations help in conveying patterns, trends, and relationships that might not be immediately apparent from raw data. Spatial data such as the results of the analogues and their corresponding locations were presented using maps. Other quantitative data and results were presented using tables and graphs.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Presentation of Results

4.1.1 Trends and Time Series analysis (Mann-Kendall trend test)

Mann-Kendall trend test is used to perceive statistically significant decreasing or increasing trends in long-term temporal data. A positive S value means that the trend is increasing, and a negative S value means that the trend is decreasing. A positive/negative value of Z indicates an upward/downward trend.

4.1.1.1 Abuja time series and trend analysis between 1990 and 2020

The temporal trends in annual mean data for temperature and precipitation between 1990 and 2020 for the city of Abuja are presented in table 4.1. The annual average temperature for Abuja city shows an increasing trend at 5 percent significant level with p values $0.00073e^{-02}$. The magnitude of the rise in temperature is 0.26^{o}C per decade. For seasonal trends, the wet season (May to October) also shows an increasing trend of 0.2^{o}C per decade while the dry (November to April) season shows a positive trend of 0.3^{o}C for the annual average temperature at 5 percent significant level. The average annual temperature is 26.83^{o}C while maximum and minimum annual temperatures are 27.2^{o}C and 26.04^{o}C in the study period. Seasonal trends in temperature shows an increasing trend while precipitation generally shows a decrease in magnitude.

Table 4.1: Trends in Temperature and Precipitation for Abuja City

Temperature	p-value	Z	S	Precipitation	p-value	Z	S
Annual	$7.30e^{-06}$	4.4848	240	Annual	0.7336	-0.3403	-19

Trends in annual seasonal precipitation showed no statistically significant trend at 5 percent significant level with the p values greater than 0.05. Average yearly precipitation and wet season precipitation showed no statistical significance at 5 percent. Negative trend was discovered in the dry season at -1.9mm per decade. Mean precipitation is 100.16mm, maximum and minimum precipitation were recorded to be 125.4mm (2016) and 77.6mm (2011) respectively.

4.1.1.2 Lagos time series and trend analysis between 1990 and 2020

The temporal trends in annual mean data for temperature and precipitation for the city of Lagos between 1990 and 2020 are presented in table 4.2. The annual average temperature for Lagos shows an increasing trend at 5 percent significant level at 0.7^{o}C per decade. Positive trends exist in the dry and wet seasons with a magnitude of 0.04^{o}C per year at 5 percent significant**.** The mean temperature is 27.68^{o}C while maximum and minimum values are 28.02^{o}C and 26.83^{o}C respectively.

Table 4.2: Trends in Climatological Seasons for Lagos between 1990 and 2020

Temperature	**p-value**	**Z**	**S**	**Precipitation**	**p-value**	**Z**	**S**
Annual	$1.05e^{-06}$	4.8828	261	Annual	0.4644	0.73156	0.4

Trends in Lagos annual mean precipitation between 1990 and 2020 showed no statistically significant trend at 5 percent significant level with p values greater than 0.05. The annual precipitation, wet and dry seasons showed no statistically significant trend at 5 percent significant level. The results showed that the maximum, minimum and mean precipitation values for the study period are 137.9mm, 85.54mm and 114.44mm respectively.

4.1.1.3 Kano time series and trend analysis between 1990 and 2020

The temporal trends in annual and seasonal data for temperature and precipitation for the city of Kano are presented in table 4.3. The annual average temperature for Kano city shows an increasing trend at 5 percent significant level with p values at 0.002. The magnitude of the increase is 0.26^{o}C per decade while maximum and minimum temperature values are 28.19^{o}C and 26.49^{o}C in the study period. For seasonal trends, dry and wet seasons also showed a non-statistically significant trend at 5 percent**.**

Table 4.3: Trends in Climatological Seasons for Kano between 1990 and 2020

Temperature	p-value	Z	S	Precipitation	p-value	Z	S
Annual	0.00196	3.0956	160	Annual	0.08434	1.726	93

Trends in Kano's annual mean precipitation showed no significant trend at 5 percent with p-value of 0.45. The maximum, minimum and mean precipitation values for the period are 81.17mm, 46.05mm and 61.51mm respectively. The dry and wet seasons also showed no statistical significance at 0.05.

4.1.1.4 Makurdi time series and trend analysis between 1990 and 2020

The trend analysis shows that the annual mean temperature for Makurdi City is increasing at 95 percent confidence level with p values of 2.661e^{-07}. The magnitude of the increase over the study period is 0.23^{o}C per decade. The trends in annual data for precipitation and temperature for Makurdi are presented in table 4.4. The analysis also revealed that the average annual temperature value is 27.83^{o}C, maximum temperature value is 28.16^{o}C and minimum temperature value is 27.04^{o}C.

Table 4.4: Trends in Climatological Seasons for Makurdi between 1990 and 2020

Temperature	p-value	Slope	Precipitation	p-value	Slope
Annual	$2.661e^{-07}$	0.023	Annual	0.6051	0.73156

For seasonal trends, the wet season (May to October) also shows an increasing trend of 0.18°C per decade while the dry (November to April) season shows a positive trend of 0.22°C per decade at 95 percent significant level. Both seasons were statistically significant at $p < 0.05$. Trends in annual mean precipitation, dry and wet seasons between 1990 and 2020 showed no statistically significant trend at 95 percent significant level with p-values all greater than 0.05. Although a negative trend was observed in both seasons, only the dry season showed a decrease in the magnitude of -1.3mm per decade. Mean precipitation value for the study period is 106.95mm, maximum value is 121.2mm and minimum precipitation value is 92.7mm.

4.1.1.5 Benin time series and trend analysis between 1990 and 2020

The temporal trends in annual data for temperature and precipitation for the city of Benin are presented in table 4.5. The annual mean temperature for Benin City shows a positive trend at 5 percent significant level and temperature increase of 0.3°C per decade. Positive trends also exists in the dry and wet seasons with a magnitude of 0.04°C and 0.03°C per year respectively at $p < 0.05$. The mean temperature value is 27.13°C while maximum and minimum values are 27.73°C and 26.6°C respectively.

Table 4.5: Trends in Climatological Seasons for Benin between 1990 and 2020

Temperature	p-value	Z	S	Precipitation	p-value	Z	S
Annual	$1.17e^{-06}$	4.86	-19	Annual	0.7075	-0.3752	-21

Trends in Benin's annual total precipitation, dry and wet seasons shows no significant trend at 5 percent. The maximum, minimum and mean precipitation values for the period are; 200.6mm, 149.2mm and 167.5mm.

4.1.1.6 Port Harcourt time series and trend analysis between 1990 and 2020

The temporal trends in annual data for temperature and precipitation for the city of Port Harcourt are presented in table 4.6. The mean annual temperature for Port Harcourt city shows a significantly positive trend at 5 percent. The magnitude of the trend is 0.27°C per decade while the wet and dry seasons are 0.25°C and 0.29°C respectively. These indicates an increase in average temperature for both seasons at 0.05 significance level. The annual mean temperature value is 26.9°C while the maximum and minimum temperature values are 27.35°C (2016) and 26.46°C (1992).

Table 4.6: Trends in Climatological Seasons for Port Harcourt between 1990 and 2020

Temperature	p-value	z	S	Precipitation	p-value	z	S
Annual	0.000002706	4.692	251	Annual	0.06353	-1.8555	-105

Negative trends were observed in wet season and annual mean precipitation data in Port Harcourt at 0.05 significant level. The magnitude of the decrease in precipitation are -3.4mm per decade (wet season) and -14.1mm per decade (annual). Mean, maximum and minimum precipitation values are 195.63mm, 224.90mm and 178.80mm respectively. Dry and wet seasons showed no statistically significant trend at 5 percent.

4.1.2 Results of Climate Analogues

4.1.2.1 Climate analogue of Abuja under the RCP4.5 and 8.5 scenarios

Climate similarity was calculated using CMIP5 data downloaded from the portal of CCAFS for projections of future climate for total monthly precipitation and average temperature (average of 2030s) and (average of 2050s) under two RCPs 4.5 and 8.5 (mitigated and unmitigated scenarios). For each of the climate scenarios, similarity (Table 4.7) was calculated for the future climate and every

Table 4.7: Climate Analogue of Abuja

Year	Scenario	Similarity	City	State/Province	Country
2030s	RCP 4.5	0.81	Kuje	Abuja	Nigeria
	RCP 8.5	0.79	Teungo	Adamawa	Nigeria
2050s	RCP4.5	0.8	Teungo,	Adamawa	Nigeria
	RCP8.5	0.77	Touga	Basse-Kotto	CAR

The results are presented as locations with the maximum pixel indicating the highest level of similarity (Figure 4.1). Abuja is projected to have an average temperature of 26.71^{o}C and average total precipitation of 117.67mm over the future period of 2020 to 2050 under the RCP 4.5 climate scenario. This shows a 2.59^{o}C increase in temperature and a slight increase of 0.93mm in precipitation when compared to the base period of 1970 to 2000. The closest place in (1970-2000) with a climate similar to the 2030s future climate of Abuja based on the combination of average temperature and total precipitation under RCP4.5 and RCP8.5 climate scenario is presented in figure 4.1 below. Kuje in Abuja represents the closest climate in the past to the future climate (2030s) of Abuja city (RCP4.5). Under the RCP8.5 climate scenario, the place with the most similar past climate to Abuja's future climate is Teungo in Adamawa state of Nigeria. Under both climate scenarios, Places with Abuja's future climate are located towards the global south and can be found in West Africa, Central Africa and South America. The climate similarity is 81 percent for the RCP4.5 and 79 percent for RCP8.5 indicating a high level of similarity for both scenarios.

For the 2050s climate, projected climate variables show a slight increase precipitation and temperature by 1.7mm and 1.85^{o}C under the RCP4.5 climate scenario for Abuja. A decrease of (-6.05mm) for precipitation and (-4.79^{o}C) for temperature is seen under the RCP8.5 climate scenario. Similar place to the future climate of Abuja in the 2050s under the RCP4.5 and 8.5 are Teungo, Adamawa state, Nigeria (80 percent level of similarity) and Touga, Ouham Pende, Central African Republic (77 percent level of similarity).

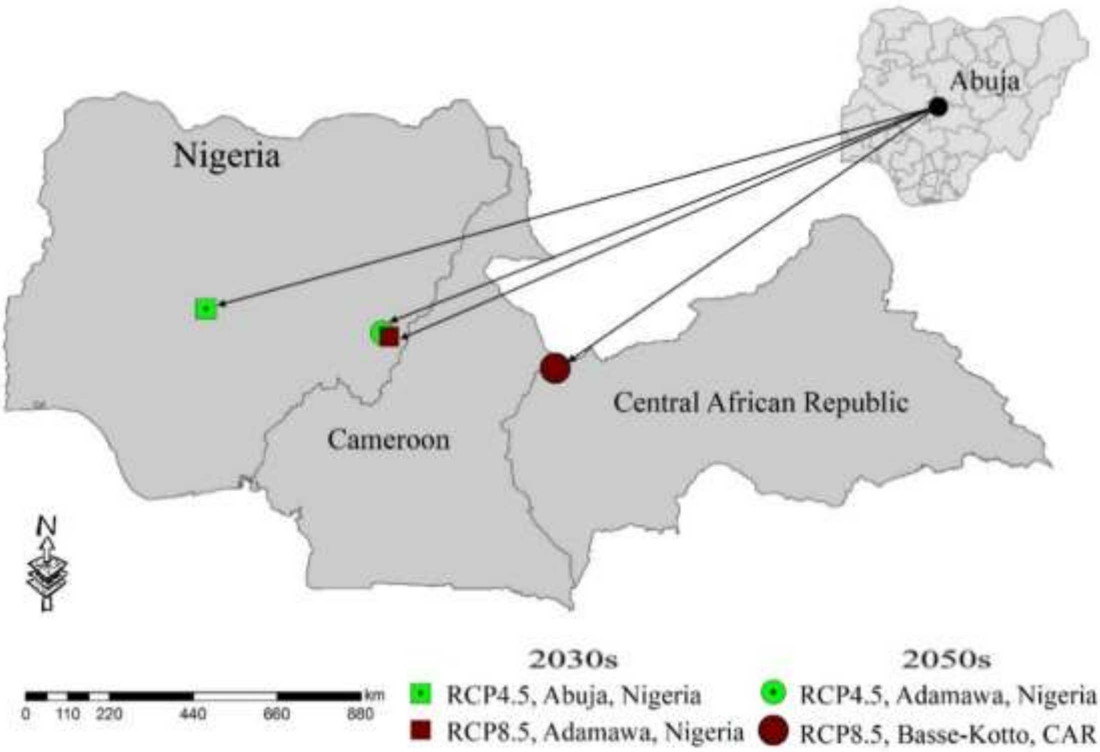

Figure 4.1: Climate of Abuja in (2030s) and (2050s)

4.1.2.2 Climate analogue of Lagos under the RCP4.5 and 8.5 scenarios.

The closest place with similar climate to Lagos future (2030s) under the RCP4.5 climate scenario is within Lagos Figure 4.2. This is an indication that residents of Lagos will mostly will most likely experience similar climate like those experienced in 1970 to 2000. The level of similarity is 78 percent based on a combination of average annual temperature and total annual precipitation. Although precipitation is expected to slightly increase by 1.83mm and temperature by 0.52°C based on the reference period of 1970 to 2000, the closest climate to the city of Lagos is within Lagos, Nigeria. Other places with closer climate are found in West Africa, Central Africa, southern Asia and South America. Based on the RCP8.5 climate scenario, the closet place with climate similar to the future climate of Lagos in 2030s is also within Lagos, Nigeria. The precipitation in 2030s is projected to decrease while temperature is projected to increase. The climate similarity between both places is 63.5 percent, thus representing a moderate level of similarity. Table 4.8 shows the project climate and closest climate to Lagos for both climate scenarios.

Table 4.8: Climate Analogue of Lagos

Year	Scenario	Similarity	City	State/Province	Country
2030s	RCP 4.5	0.78	Lagos	Lagos	Nigeria
	RCP 8.5	0.64	Lagos	Lagos	Nigeria
2050s	RCP4.5	0.64	Obanikoro	Lagos	Nigeria
	RCP8.5	0.61	Alto da Mira	Camacari	Brazil

For the 2050s climates, the city of Lagos has a climate similar to itself for the RCP4.5 climate scenario while Camacari, Bahia in Brazil has the closest climate under the 8.5

climate scenario to the future city of Lagos. The level of similarity scores are 64 percent (RCP4.5) and 61 percent (RCP8.5) (Table 4.8). This level of similarity is moderate, therefore, should not be best described as a good analogue for Lagos for the 2050s climate. Temperature and precipitation projections for the 2050s climate when compared with the baseline period shows a decrease (-4.61mm) (RCP4.5), (-3.58mm) (RCP8.5) and an increase in temperature 1.18^{o}C (RCP4.5) to 2.6^{o}C (RCP8.5).

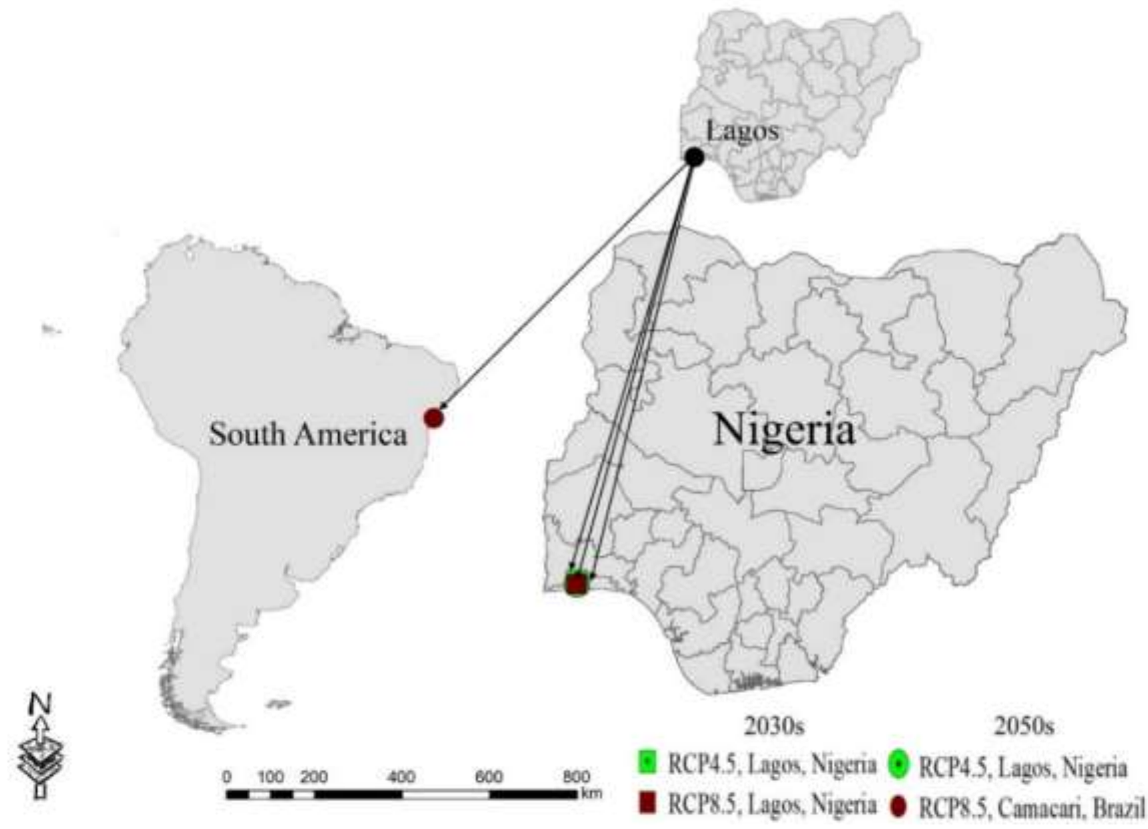

Figure 4.2: Climate of Lagos (2030s) and (2050s)

4.1.2.3 Climate analogue of Kano under the RCP4.5 and 8.5 scenarios

Temperature and precipitation projections for Kano, Nigeria show an increase of 9.14mm and 1.17^{o}C under the RCP 4.5, 8.97mm and 1.87^{o}C under the RCP 8.5 climate scenario in the 2030s. The closest climate similar to Kano based on the combination of precipitation and temperature (2030s) for RCP4.5 and RCP8.5 are Kollere in Yobe State, Nigeria (68 percent) and Mukjar in West Darfur, Sudan (66 percent) (Table 4.9). The level of similarity is moderate and can therefore not be regarded as the optimum. Projections for climate variables in 2050s also shows an increase in both precipitation and temperature for both RCPs over the city of Kano.

Table 4.9: Climate Analogue of Kano

Year	Scenario	Similarity	City	State/Province	Country
2030s	RCP 4.5	0.68	Kollere	Yobe	Nigeria
	RCP 8.5	0.66	Mukjar	West Darfur	Sudan
2050s	RCP4.5	0.65	Burunga	Darfur	Sudan
	RCP8.5	0.65	Zalingei	Darfur	Sudan

Precipitation is projected to increase by 7.93mm and 9.33mm for RCPs 4.5 and 8.5 respectively; while temperature is projected to increase by 2.09^{o}C and 3.02^{o}C for RCP4.5 and RCP8.5 respectively. Burunga in West Darfur, Sudan with 66 percent similarity and Zalingei, central Darfur, Sudan (66 percent similarity) are the most similar to the climate of Kano by 2050s for RCPs 4.5 and 8.5. The level of similarity is moderate and should therefore not be regarded as optimum. Table 4.11 shows the future climates for Kano city, while figure 4.3 shows the locations.

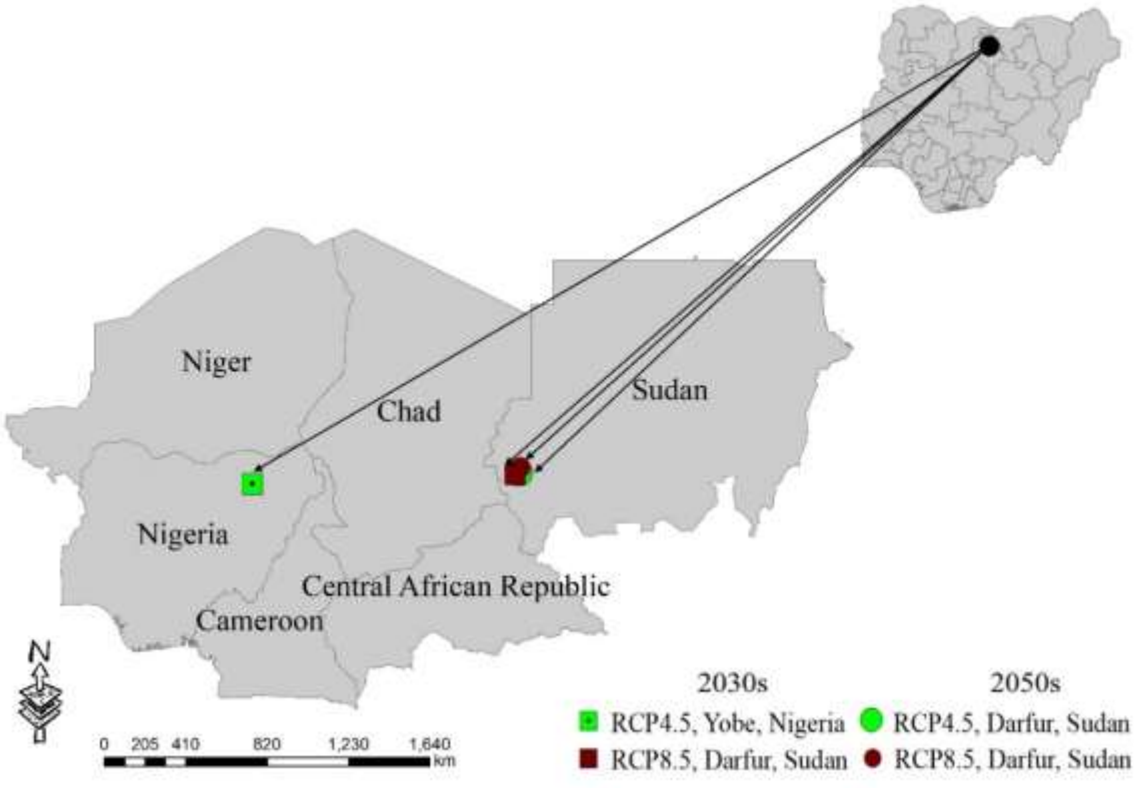

Figure 4.3: Climate of Kano (2030s) and (2050s).

4.1.2.4 Climate analogue of Makurdi under the RCP 4.5 and 8.5 scenarios

The closest climate to the climate of Makurdi based on the combination of temperature and precipitation for 2030s climate are Jato, Kogi State, Nigeria (RCP4.5) at 77 percent similarity level and Bali, Taraba State, Nigeria (RCP8.5) at 76 percent similarity level. The threshold is considered high and therefore can be considered as very close to the future climate of Makurdi (Table 4.10).

Teungo, Adamawa state, Nigeria is most similar under the RCP 4.5 climate scenario at 74 percent similarity level to the future climate of Makurdi while, Bali, Taraba State, Nigeria is closest under the RCP8.5 scenario at 74 percent in the 2050s climate. 74 percent similarity level is considered to be moderately similar and therefore should not be considered as an appropriate representation of climate analogues for Makurdi. Table 4.10

shows the current and projected climate variables of Makurdi and the places with similar climate.

Table 4.10: Climate Analogues of Makurdi

Year	Scenario	Similarity	City	State/Province	Country
2030s	RCP 4.5	0.77	Jato	Kogi	Nigeria
	RCP 8.5	0.76	Bali	Taraba	Nigeria
2050s	RCP4.5	0.74	Teungo	Adamawa	Nigeria
	RCP8.5	0.74	Bali	Taraba	Nigeria

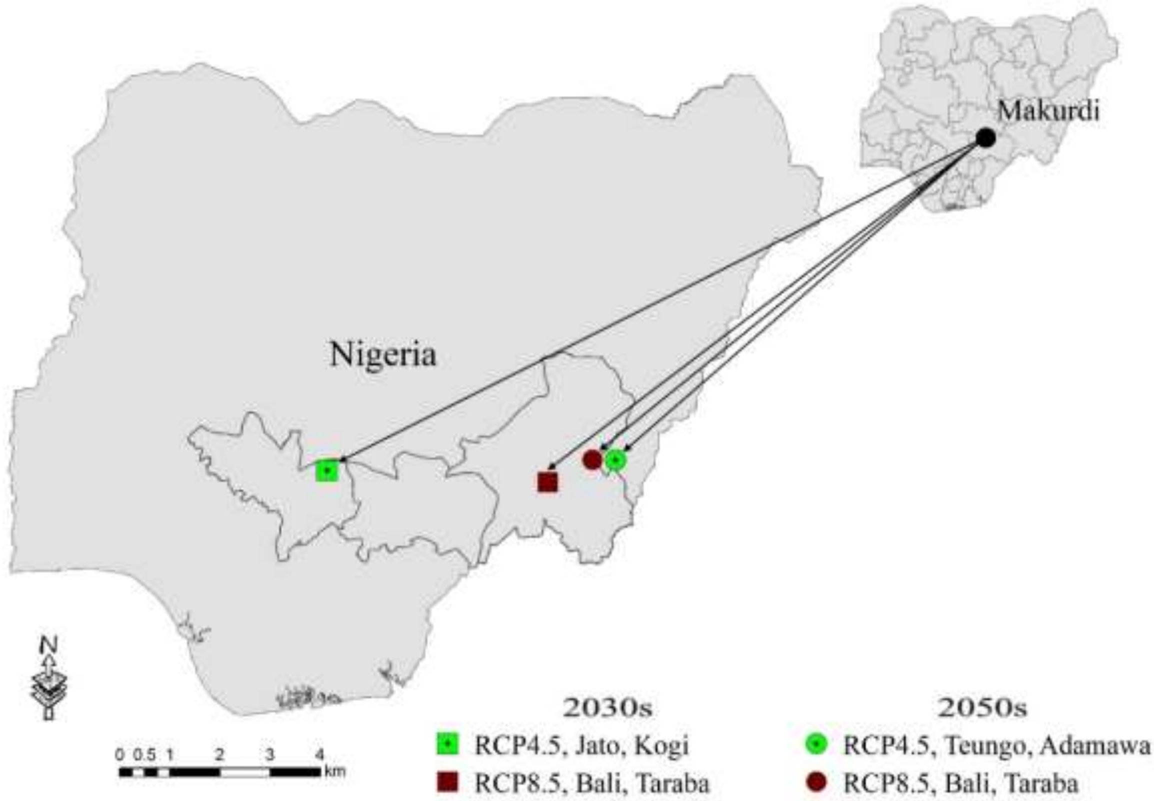

Figure 4.4: Climate of Makurdi (2030s) and (2050s)

4.1.2.5 Climate analogue of Benin under the RCP4.5 and 8.5 scenarios

Contemporary climate for the city of Benin in the 2030s based on a combination of precipitation and temperature under the RCP4.5 and RCP8.5 climate scenarios can be found in Benin, Nigeria (68 percent similarity level) and Bouagleu, Tonkpi, Cote d'ivoire (80 percent) respectively (Table 4.11). The RCP4.5 climate scenario is regarded as a better analogue due to the high level of similarity, while the RCP8.5 scenario cannot be regarded as optimum due to the similarity score. Projected temperature in Benin is expected to slightly decrease by (-0.22^{o}C) (RCP4.5) and (-4.33) (RCP8.5^{o}C) while precipitation is projected to increase in both climate scenarios.

Table 4.11: Climate Analogues of Benin

Year	Scenario	Similarity	City	State/Province	Country
2030s	RCP 4.5	0.8	Bouagleu	Tonkpi	Côte d'Ivoire
	RCP 8.5	0.68	Benin	Edo	Nigeria
2050s	RCP4.5	0.67	Nyampleu	Tonkpi	Côte d'Ivoire
	RCP8.5	0.69	Douapleu	Tonkpi	Côte d'Ivoire

For 2050s climate, Benin’s closest climate for the base period of 1970 to 2000 for RCP4.5 (67 percent) and RCP 8.5 (69 percent) are in Tonkpi, Cote d’ivoire. The level of similarity is moderate for both climate scenarios but the result shows that the climate based on a combination of temperature and precipitation for 2050s looks alike for both climate scenarios. The projected climate variables show an increase of 1.11^{o}C in temperature and a decrease in precipitation of (-5.69^{o}C) for the RCP4.5 climate scenario. Table 4.11 shows the future climates for Benin City, while figure 4.5 shows the locations.

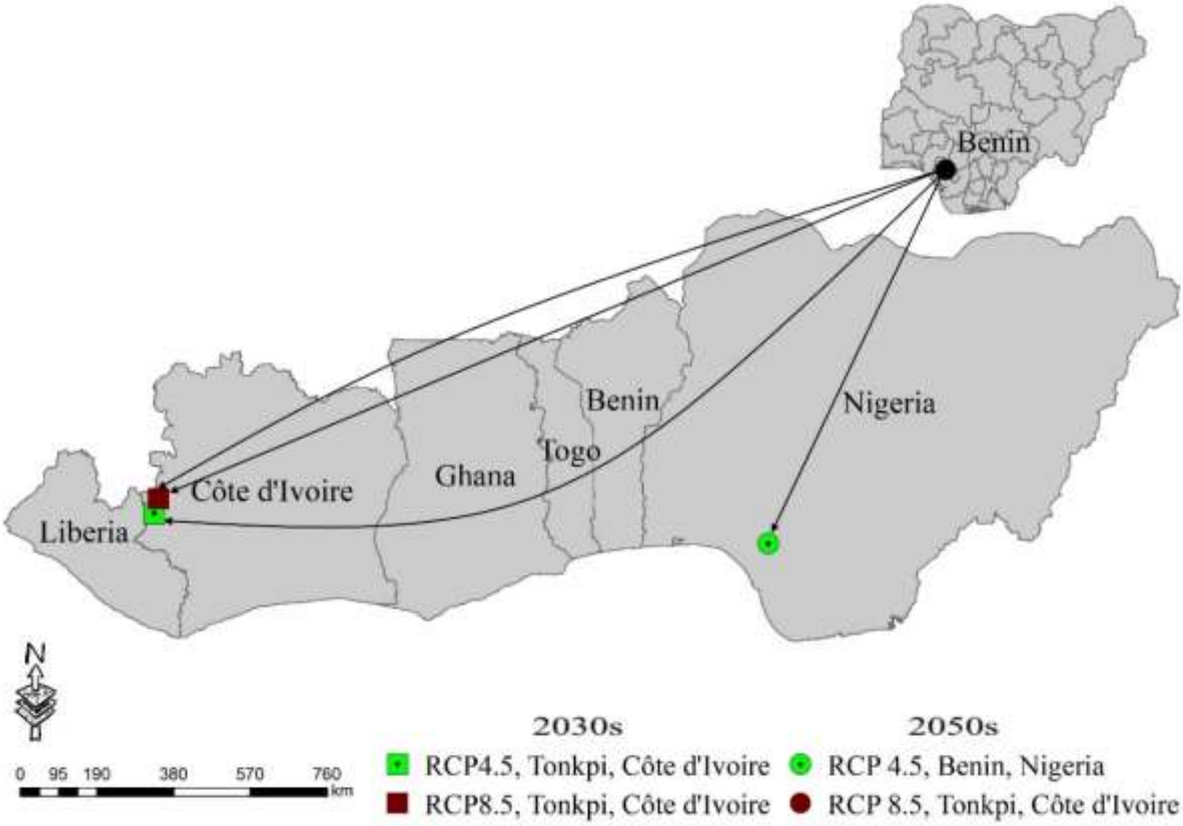

Figure 4.5: Future Climate of Benin (2030s) and (2050s)

4.1.2.6 Climate analogue of Port Harcourt under the RCP 4.5 and 8.5 scenarios

Similar climate to that of Port Harcourt in 2030s are located in Akamkpa, Cross Rivers Syaye, Nigeria for RCP4.5 and 8.5 climate scenarios (Table 4.12).

Table 4.12: Climate Analogues of Port Harcourt

Year	Scenario	Similarity	City	State/Province	Country
2030s	RCP 4.5	0.74	Akamkpa	Cross River	Nigeria
	RCP 8.5	0.75	Akamkpa	Cross River	Nigeria
2050s	RCP4.5	0.71	Mudemba	Ndian	Cameroon
	RCP8.5	0.69	Akamkpa	Cross Rivers	Nigeria

The results shows that based on the combination of precipitation and temperature (climate), Port Harcourt's climate would look like Akamkpa under both scenarios. Projected temperature shows an increase of 1.11^{o}C (RCP 4.5) and decrease of (-3.06^{o}C) (RCP 8.5) while projected precipitation shows a decrease of (-2.8mm) (RCP4.5) and increase of 2.75 (RCP8.5). Places with closest climate to that of Port Harcourt in the 2050s climate under the RCPs 4.5 and 8.5 climate scenario are found in Mudemba, Ndian, Cameroon and Akampka, Cross Rivers, Nigeria based on the combination of temperature and precipitation. Figure 4.6 shows the locations of the current and future climates for Port Harcourt City.

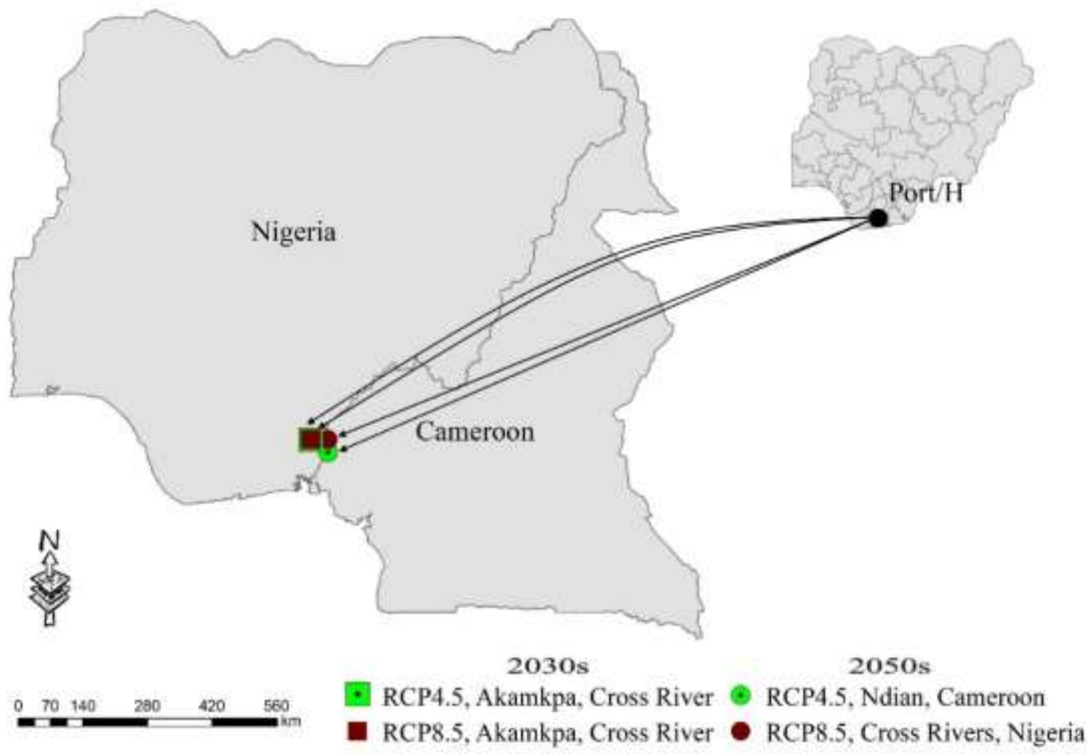

Figure 4.6: Future Climate of Port Harcourt (2030s) and (2050s)

4.1.3 New Climates of the Cities under the Climate Scenarios

To identify cities with new climate in the 2030s and 2050s period, a similarity score that is low represents a condition where the climate of the cities does not look like any place in the current and future periods. A similarity score of 1 indicates a perfect match in the climatic conditions of the analogue while a similarity score of 0 indicates a no similarity. For the 2030s period Abuja had the highest level of similarity (0.8) meaning that the conditions of Abuja city look more like the conditions of its analogue. The city of Kano on the other hand had the lowest level of similarity of all the cities examined, this is an indication that the city of Kano is moving towards novelty and can therefore cannot be considered as the best representation of the Kano future and current climatic conditions. Figures 4.7 and 4.8 shows the comparison of similarity score for the RCPs in the 2030s and 2050s periods.

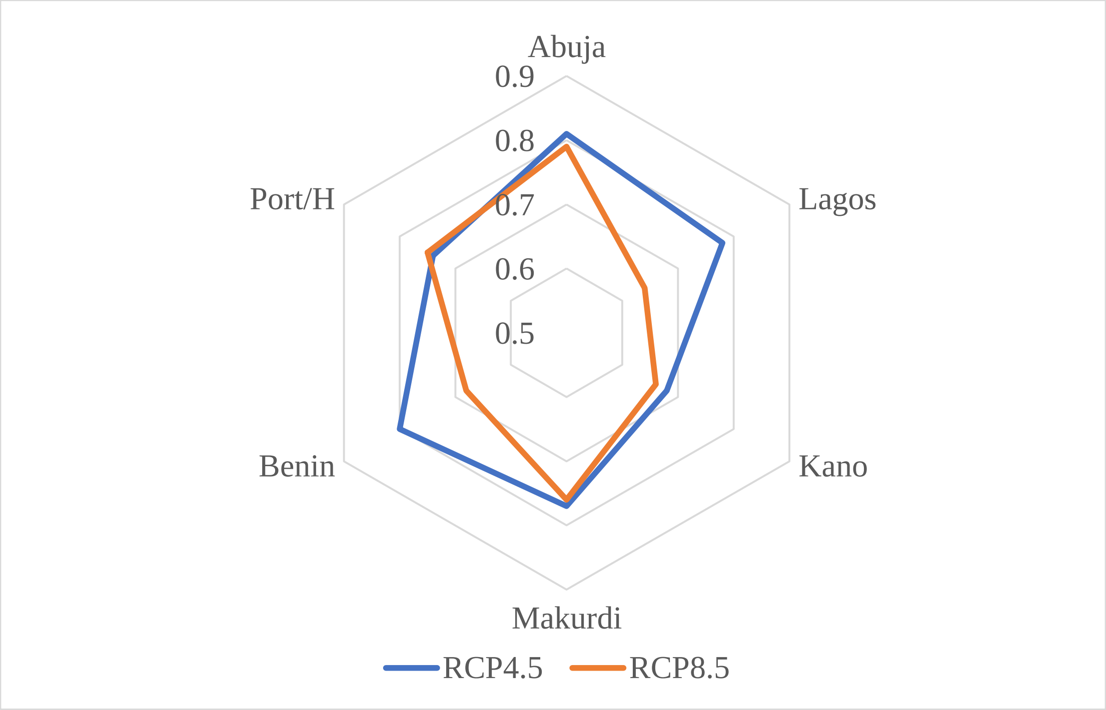

Figure 4.7: Similarity Score of 2030s Climate Analogues

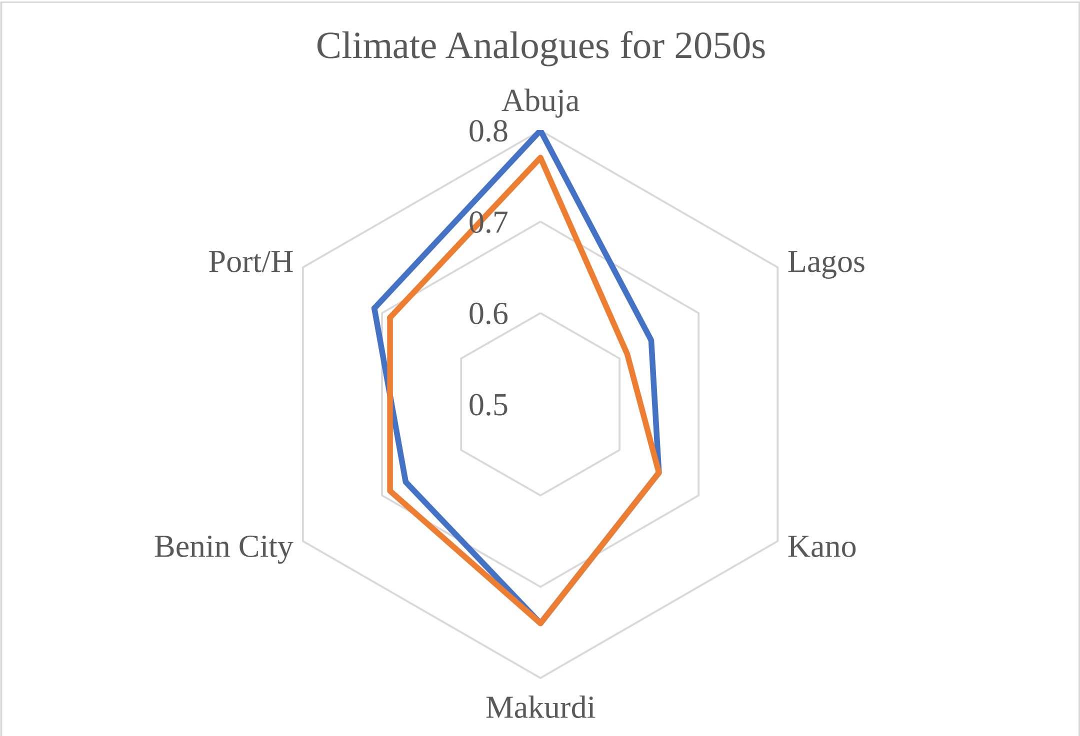

Figure 4.8: Similarity Score of 2050s Climate Analogues

4.1.4 Temperature Analogues of the Cities

Figures 4.9 and 4.10 show the similarity map and score respectively for the 2030s periods while Figures 4.11 and 4.12 show the similarity map and score respectively for the 2050s periods. These shows the overview of the cities and their shifts in temperature for the current period of 2021-2050 and the future period of 2041-2070 under the RCP4.5 and 8.5 scenarios. The arrows from the figures show the direction of the city shifts to temperature conditions most similar to their current and future conditions in the historical period of 1971-2000. Locations in green represent the scenario where climate policies on emission reduction are undertaken while red represents the scenario where greenhouse emissions continue to rise throughout the twenty-first century. The locations of the cities are represented as follows; a. Kano b. Abuja c. Makurdi d. Benin e. Lagos f. Port Harcourt

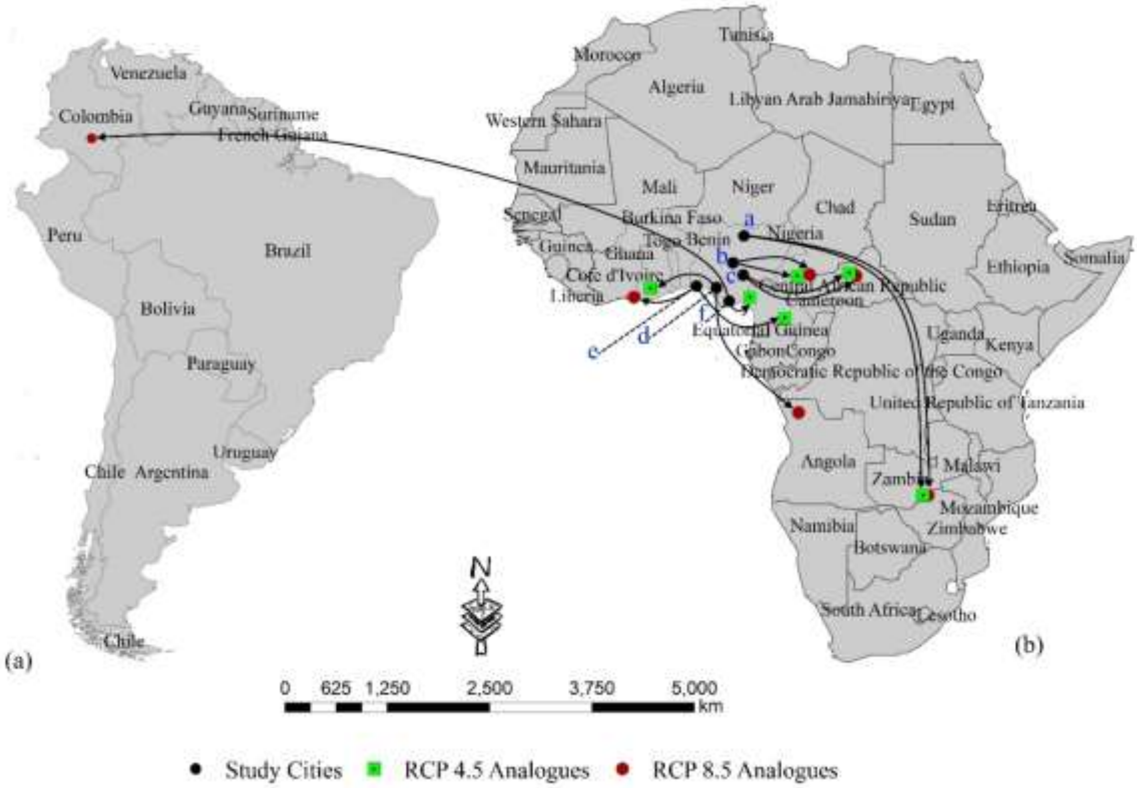

Figure 4.9: Temperature analogues for the 2030s (RCP4.5 and 8.5 scenarios)

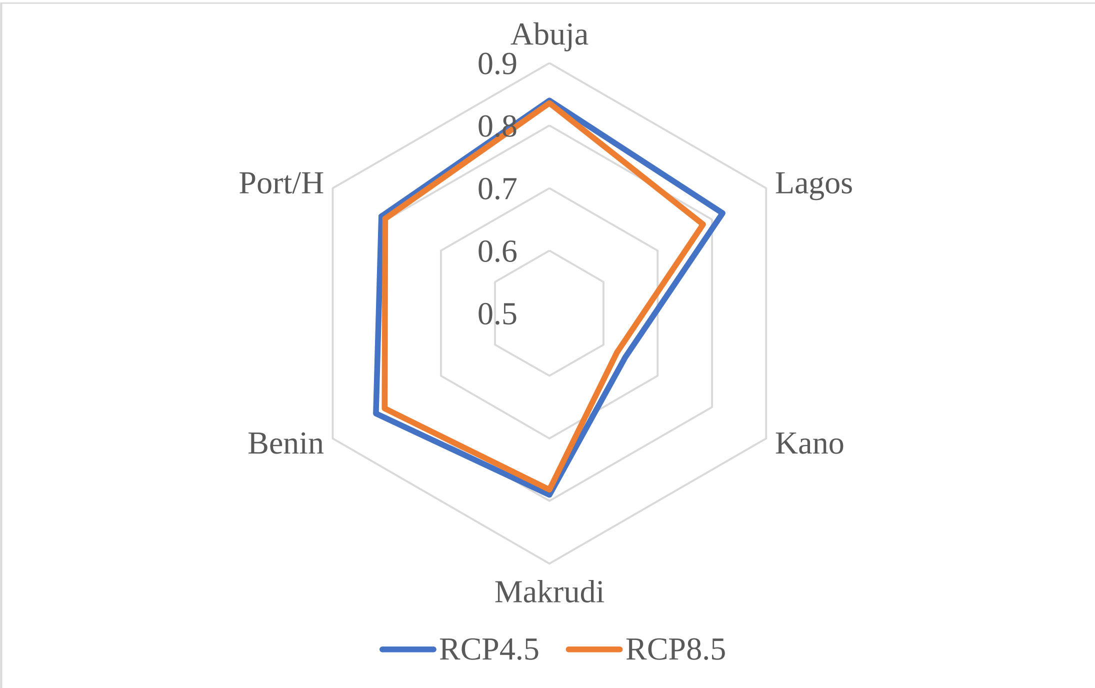

Figure 4. 10: 2030s Temperature Similarity for the Cities

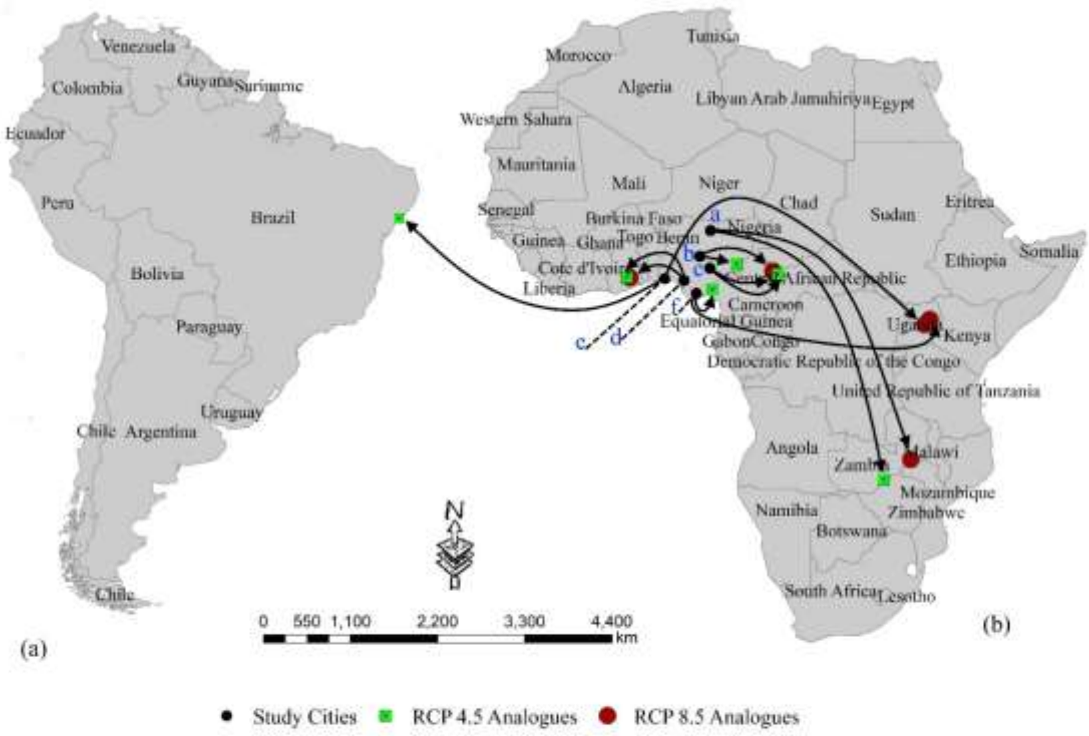

Figure 4.11: Temperature analogues for the 2050s (RCP4.5 and 8.5 scenarios)

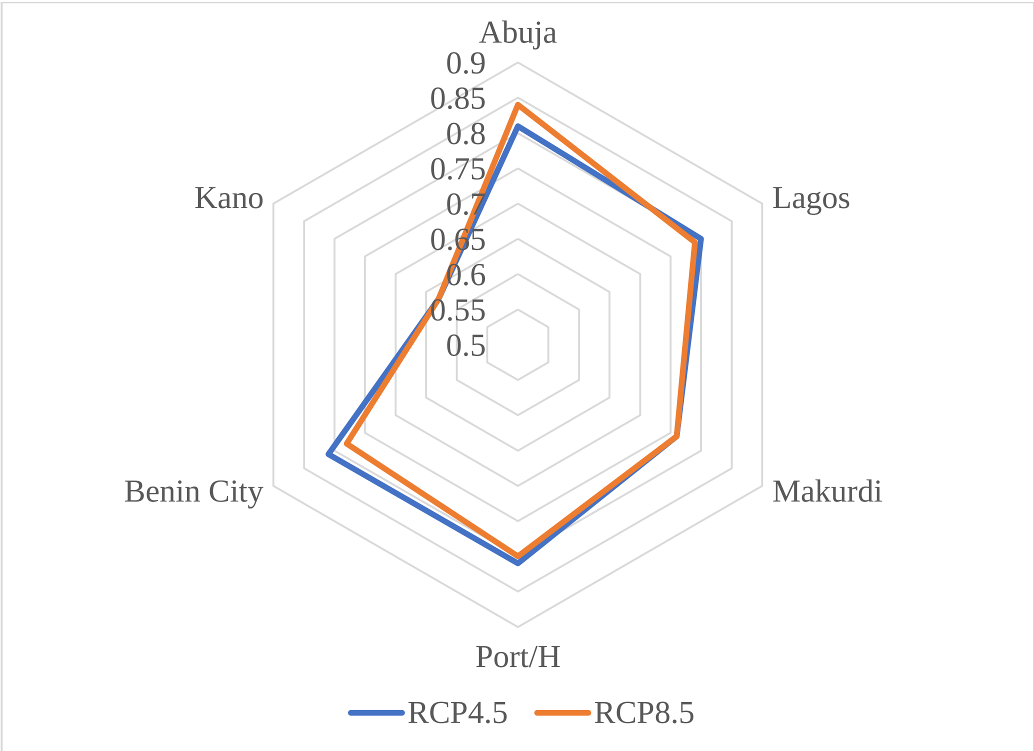

Figure 4.12: 2050s Temperature Similarity for the Cities

a. Kano

The similarity surface shows that Kano's current average temperature conditions for the historical period resides in the southern part of Africa near Siavonga in Zambia although with a lower similarity level (0.64) when compared to other cities (Table 4.13). This is an indication of temperature novelty meaning current conditions will look like what has not been experienced in the baseline period. The unmitigated scenario (RCP8.5) shows that the analog is located further south in Zimbabwe, around Mashonaland (0.63) which is about 3,867Km in the South-east direction from Kano. These similarity values are not the best for the representation of Kano's current temperature indicating a changing climate. This also points to the fact that under the scenario most in line with what might be expected given current policies and the speed of global action, Kano's temperature will shift further south and temperature novelty will increase.

b. Abuja

In the current temperature conditions for the mitigation scenario, Abuja will become similar to the 1971-2000 temperature located hundreds of kilometer (789km) in the south-east direction from Abuja around Meyo-Rey, Northern Province of Cameroon. Without climate mitigation (RCP8.5 scenarios), the average temperature is closest to somewhere around Logone oriental in southern Chad (similarity score of 0.84). We observed similar results in the 2050s averages with Abuja's future for the unmitigated scenario more like temperatures found in Central African Republic around Ngaoundaye (Table 4.13).

c. Makurdi

The most similar for the 2030s period in both scenarios are located around Bamingui-Bangoran in Central African Republic implying that with or without mitigation, Makurdi's average temperature do not change for the future periods. In the 2050s, most of the places with similar temperature in both scenarios are located within the tropics of

Africa (Paoua with a similarity score of 0.76 and about 857km away in the Central African Republic in the RCP4.5 scenario and around Bocaranga in the Central African in the RCP8.5 (Table 4.13).

d. Benin

The most similar place with a similarity value of 0.82 is located along the coast of West Africa around the Ashanti Region of Ghana while the RCP8.5 scenario show the best representation near Uige in Angola (0.80). The 4.5 scenario show a higher level of similarity when compare to the 8.5, although both scenarios are considered to be good analogues of temperature for Benin (Table 4.13).

e. Lagos

Contemporary temperature analogues for the 2030s temperature for Lagos future under the mitigated scenario (RCP4.5) is located within West Africa in Cameroon around Haut-Nyong and within the coast of West Africa in Côte d'Ivoire near Roa, Comoe for the RCP8.5. Both scenarios average a distance of about 972 kilometres from Lagos and the similarity scores indicates changes and shifts in temperature conditions for Lagos. The 2050s average shows a good analog for both RCPs with the best located in West Africa and towards central Africa. The best analog indicating to Lagos is located far away in Brazil near Aracaju, under the mitigated scenario 4.5 while the 8.5 scenario is located in Soroti, Uganda (Table 4.13).

f. Port Harcourt

The 2030s temperature of Port Harcourt is located around Kupe-Muanenguba, S/W Region of Cameroon for the RCP 4.5 while the 8.5 scenario is near Lengupa Province of Colombia (0.80). For the 2050s, similar future temperature in the RCP 4.5 scenario is best located in Mundemba, Cameroon and further south in Budiope in Uganda for RCP 8.5 (Table 4.13).

Table 4.13: Similarity of Temperature Analogues RCP4.5 and 8.5 (2030s)

Cities			Kano (a)	Abuja (b)	Makurdi (c)	Benin (d)	Lagos (e)	Port Harcourt (f)
Current Period 2030s	RCP4.5	Similarity Scores	0.64	0.84	0.79	0.82	0.82	0.81
		Analog	Siavonga, Zambia	North Province, Cameroon	Bamingui-Bangoran, Central African Republic (CAR)	Ashanti Region, Ghana	East Province, Cameroon	South-west Region, Cameroon
	RCP8.5	Similarity Scores	0.63	0.84	0.79	0.8	0.78	0.8
		Analog	Mashonaland , Zinbabwe	Logone Oriental, Chad	Bamingui-Bangoran, CAR	Ugie Provice, Angola	Comoe, Côte d'Ivoire	Lengupa Province, Colombia
Future Period 2050s	RCP4.5	Similarity Scores	0.65	0.81	0.76	0.81	0.8	0.81
		Analog	Chikankanta, Zambia	Adamawa, Nigeria	Paoua, CAR	Kwahu East, Ghana	Aracaju, Brazil	Mundemba, Cameron
	RCP8.5	Similarity Scores	0.63	0.84	0.76	0.78	0.79	0.8
		Analog	Petauke, Zambia	Ngaoundaye, CAR	Bocaranga, CAR	Kwahu South, Ghana	Soroti, Uganda	Budiope, Uganda

4.1.5 Precipitation Analogues of the Cities

Precipitation analogues for the studied cities in the 2030s periods under the RCP4.5 climate scenario is located within their respective cities except for the city of Port Harcourt (Figure 4.13 (Similarity Map)) which is located in Bong, Liberia. This shows that precipitation conditions for the current period of 2030s will not change to another place. Given the scenario best in lines with business as usual (RCP8.5), precipitation analogues for the studied cities in the 2030s periods are located within their respective cities except for the city of Abuja (b), which is located in the Kara region of Togo. This is an indication that precipitation conditions in the cities for the scenario will not change to another place. Figure 4.14 shows the Similarity Scores while the, precipitation analogues of the cities are represented as follows; a. Kano b. Abuja c. Makurdi d. Benin e. Lagos f. Port Harcourt.

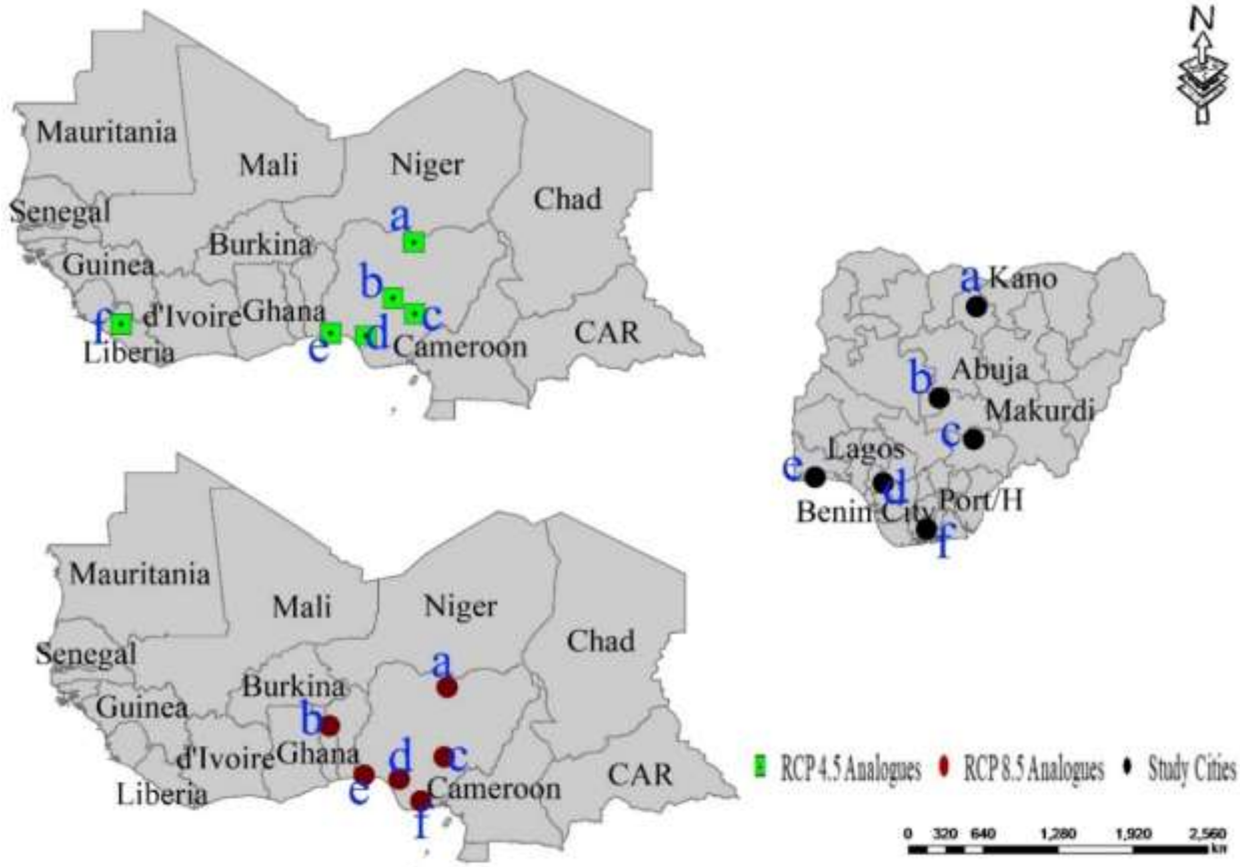

Figure 4.13: Precipitation Analogues for 2030s

a. Kano b. Abuja c. Makurdi d. Benin e. Lagos f. Port Harcourt

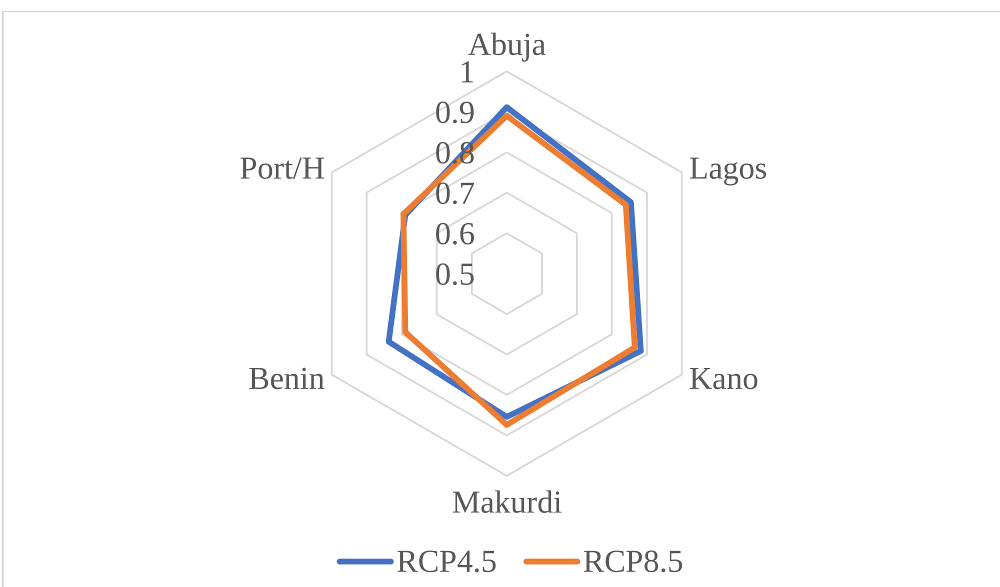

Figure 4.14: 2030s Precipitation Similarity for the Cities

The places with the most similar precipitation conditions closest to the conditions of the selected cities under the RCP 4.5 scenario and in the 2050s periods are found within the same with an exception of Abuja, which is located in Kara region of Togo and Makurdi, which is located in Bali, Taraba state, Nigeria (Figure 4.15 (Similarity Map) and Figure 4.16 (Similarity Scores). While for the unmitigated scenario (RCP 8.5), Abuja is the only with precipitation analogue located outside its region (Uttaradit province of Thailand). All the other cities' precipitation analogues are located within the same state. The similarity scores for each of the cities are presented in table 4.14 while the locations and precipitation analogues of the cities are represented as follows; a. Kano b. Abuja c. Makurdi d. Benin e. Lagos f. Port Harcourt.

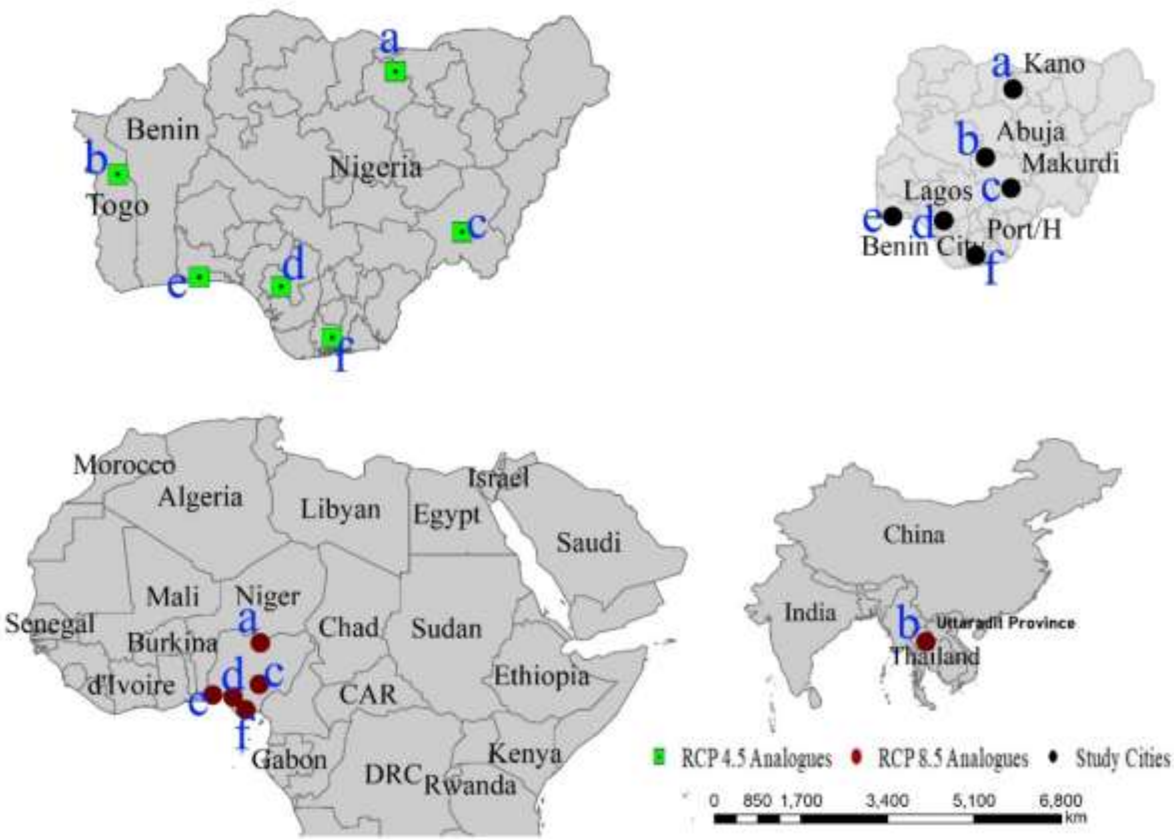

Figure 4.15: Precipitation Analogues for 2050s.

a. Kano b. Abuja c. Makurdi d. Benin e. Lagos f. Port Harcourt

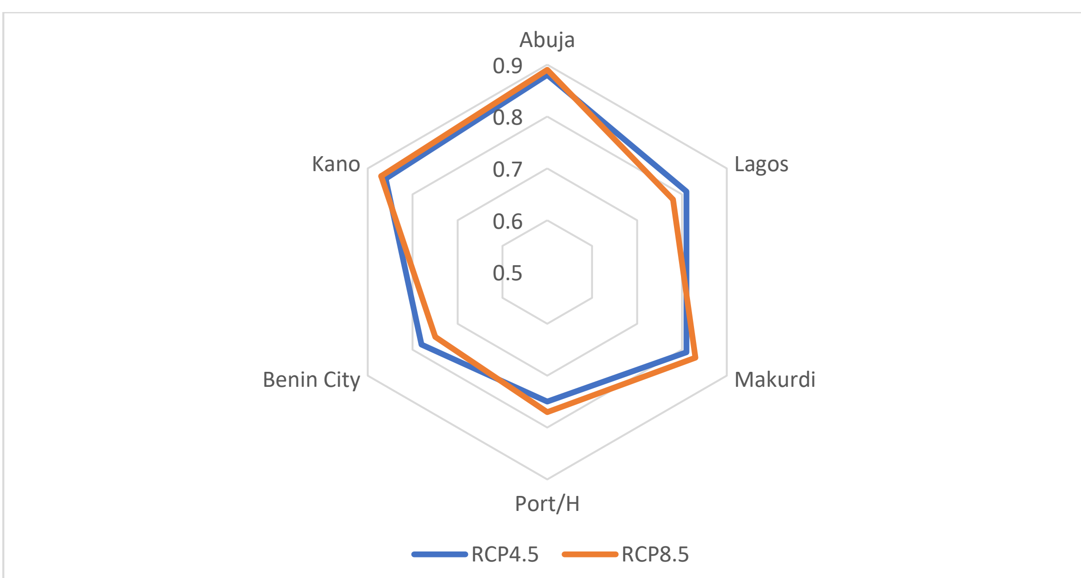

Figure 4.16: 2050s Precipitation Similarity for the Cities

Table 4. 14: Similarity of Precipitation Analogues RCP4.5 and 8.5 (2030s)

Cities			Kano (a)	Abuja (b)	Makurdi (c)	Benin (d)	Lagos (e)	Port Harcourt (f)
Current Period 2030s	**RCP4.5**	**Similarity Scores**	0.88	0.91	0.85	0.84	0.85	0.79
		Analog	Guma, Kano, Nigeria	Kuje, Abuja, Nigeria	Fuamah, Benue, Nigeria	Oredo, Edo, Nigeria	Obanikoro, Lagos, Nigeria	Bong, Liberia
	RCP8.5	**Similarity Scores**	0.87	0.89	0.87	0.79	0.84	0.79
		Analog	Kano, Nigeria	Kara Region, Togo	Makurdi, Benue, Nigeria	Benin, Edo, Nigeria	Lagos, Nigeria	Port/Harcourt, Nigeria
Future Period 2050s	**RCP4.5**	**Similarity Scores**	0.86	0.88	0.81	0.78	0.81	0.75
		Analog	Gabassawa, Kano, Nigeria	Kara, Togo	Bali, Nigeria	Etet, Edo, Nigeri	Lagos, Nigeria	Umuehere, Port Harcourt, Nigeria
	RCP8.5	**Similarity Scores**	0.87	0.89	0.83	0.75	0.78	0.77
		Analog	Dambatta, Kano, Nigeria	Uttaradit Province, Thailand	Makurdi, Nigeria	Etet, Edo, Nigeria	Lagos, Nigeria	Umuehere, Port Harcourt, Nigeria

4.1.6 Climate Indices for the Cities

Results of the analysis of extreme in climate (temperature and precipitation) for the six cities are presented in this section. Precipitation and temperature-based indices are computed on the annual scale. The selected indices reflects climate impacts on urban residents such as water availability, dryness, heating, cooling and other related indices. Specifically, the estimated precipitation indices focus on total precipitation accumulations, threshold-based rainfall events and maximum rainfall extremes. Indices of cold and warm extremes of daily minimum temperature (TN) and daily maximum temperature (TX), percentile-based thresholds, and fixed threshold exceedances are reported for each of the cities. Cold spell duration index (CSDI) and warm spell duration index (WSDI) as a function of changes in cold and warm spells were also examined for the cities from 1991 to 2020.

4.1.6.1 Temperature indices

Minimum temperature in all the cities over the period shows positive significant trends at $p \leq 0.05$ confidence level and ranges between an increasing 0.4 to 0.1°C per decade from North to south while maximum temperature shows a positive trend for cities inland (Kano and Abuja) at 0.8°C and 0.7°C respectively reflecting warming. Lagos indicated a slightly negative trend at 0.04°C per decade Maximum temperature changes are also dominated by a general distributional shift toward warmer temperatures over all the cities. The tabulated result (Table 4.15 and Table 16) shows cities with increasing and decreasing trend values. The significance level under 95 percent level of confidence of each value is indicated under the significance. Figure 4.17 shows the comparison in the magnitude of change for each of the cities.

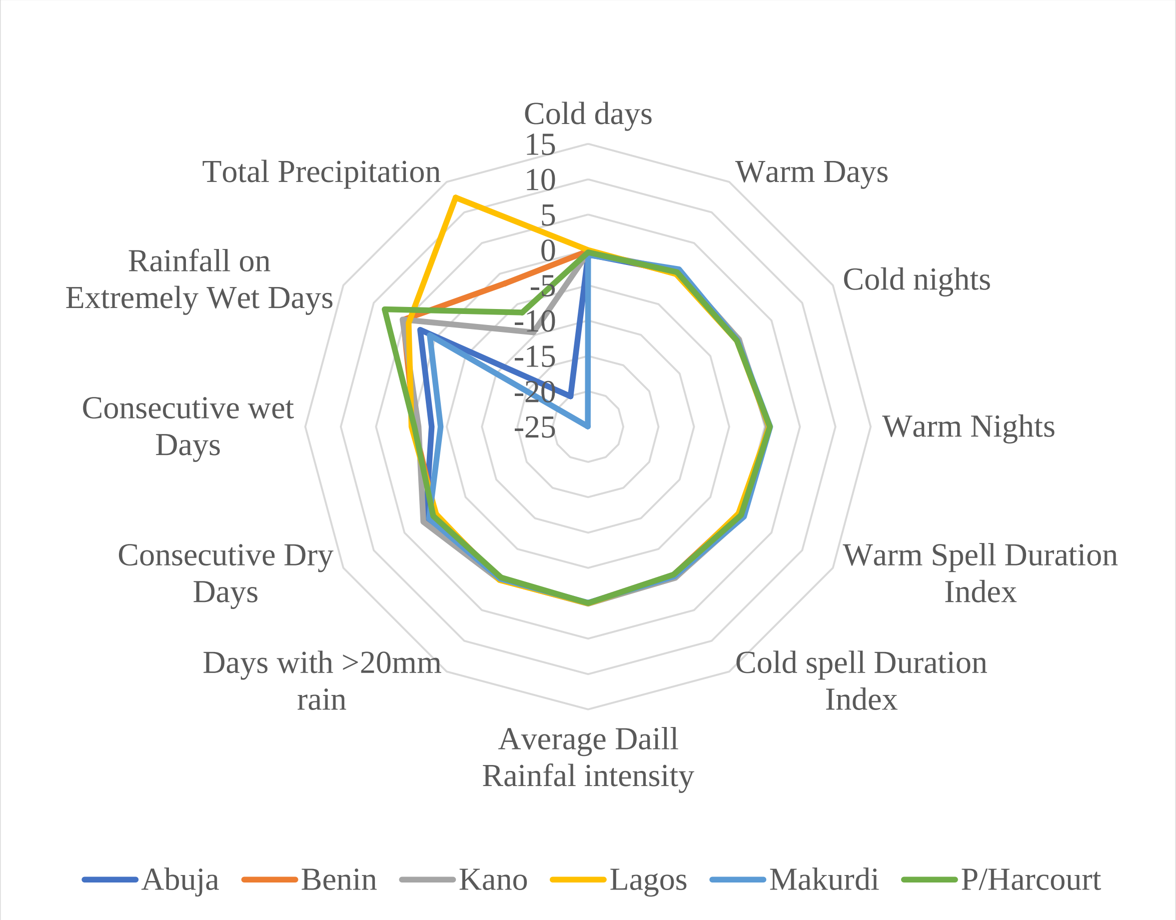

Figure 4.17: Magnitude of Change in Climate Indices for the Cities

Table 4.15: Temperature indices for Kano, Abuja and Lagos

Indices	Unit	Indicator	Kano		Abuja		Lagos	
			Slope	**P-Value**	**Slope**	**P - value**	**Slope**	**P-Value**
Cold days	Days	TX10p	-0.371	0.006*	-0.662	0*	-0.026	0.802
Warm Days	Days	TX90p	0.476	0.008*	0.287	0.258	-0.083	0.572
Cold nights	Days	TN10p	-0.336	0.003*	-0.54	0*	-0.64	0*
Warm Nights	Days	TN90p	0.46	0.004*	0.617	0.001*	0.645	0.001*
Warm Spell Duration Index	Days	WSDI	0.419	0.21	0.001	0.997	-0.387	0.02*
Cold spell Duration Index	Days	CSDI	-0.311	0.046*	-0.749	0*	-0.64	0.018*

* Statistically Significant

Table 4.16: Temperature Indices for Makurdi, Benin and Port Harcourt

Indices	Unit	Indicator	Makurdi Slope	Makurdi P-Value	Benin Slope	Benin P - value	Port Harcourt Slope	Port Harcourt P-Value
Cold days	Days	TX10p	-0.72	0*	-0.662	0*	-0.153	0.066
Warm Days	Days	TX90p	0.714	0.001*	0.287	0.258	-0.004	0.982
Cold nights	Days	TN10p	-0.563	0*	-0.54	0*	-0.608	0*
Warm Nights	Days	TN90p	0.777	0*	0.617	0.001*	0.684	0*
Warm Spell Duration Index	Days	WSDI	0.493	0.043*	0.001	0.997	-0.358	0.249
Cold spell Duration Index	Days	CSDI	-0.543	0.008	-0.749	0	-0.745	0.001*

* Statistically Significant

a) **Temperature indices for Kano**

The annual maximum temperature indicates significant positive trend at 0.6°C per decade while the minimum temperature indicates a 0.4°C increase per decade. This points to warming. Total Precipitation (PRCPTOT) show no statistical significant trend at $p \leq 0.05$. Warmest day TXx which signify the hottest days is been observed to increase within the period of 1991 to 2020. Statistically significant trend and a 0.4°C increase per decade is present in TXx compared to warmest night TNx 0.5°C increase per decade. An increasing trend in TNx- maximum value of daily minimum temperature during the period at 5 percent significant level is observed. The number of warm days (TX90p) and Nights (TN90p) have also increased with an average of 10 days each in the 30 years' period in Kano. The trends are statistically significant. The significance of TXn and TNn trend is not as strong as those seen for the other indices for temperature extremes (TNx and TXx). Coldest day TXn and night TNn indicated no statistically significant trend at 95 percent confidence level. Cold nights TN10p which is the number of cold nights presents significant downtrend for Kano at the rate of (-3.3 °C/decade) and an average of 10 days for the period. The average number of cold days TX10P is 10.5 day during the period with a magnitude of 3.7°C per decade. A significant decreasing trend was present. There are significant decreasing trends in the frequencies of cool days and nights, and significant increasing trends in warm days and nights. Cold spell duration index CSDI which informs when the minimum temperature (TN) remains below its 10th percentile presents a slightly decreasing trend at $p \leq 0.05$ and a magnitude of (-0.3 °C per year) while the average number of days for CSDI within the period is 6.5 days. The average value for the Warm spell duration index is 10.4 days during the period, and no significant trend was present.

b) Temperature indices for Abuja

Maximum and minimum temperature indicates a slightly increasing trend of 0.79°C and 0.49°C per decade respectively. Warmest day TXx index which represents hottest days during the period 1991-2020 shows a slightly increasing trend at a magnitude of 0.1°C/year. The level of significance is consistent with that of the warmest night TNx (magnitude of 0.07°C/year) at 95 percent confidence level. Significant trends seen in Txn and TNn are not as strong as those seen for the other indices for temperature extremes (TXx, TNx and TN90p). TN90P - The frequency of occurrence of warm nights has an average of 10.6 days and a significantly positive trend while warm days TX90p was found to have no statistically significant trend at $p \leq 0.05$ during the period. The warm spell duration index WSDI has no evidence of a significant trend. Coldest night TXn and day TNn was found to have positive trends that are statistically significant. The average value of TXn is 22.5°C and a magnitude of 0.31°C increase per decade while TXn which represents the minimum value of daily maximum temperature has a magnitude of 0.3°C increase per decade for Abuja. TN10p - The number of cold nights (average of 10 days) indicates a strong significant negative trend of (-5.4°C per decade) while TX10P which is the number of cold days is found to also decrease with a magnitude of (-6.6°C per decade). Cold spell duration index CSDI has a decreasing and significant trend (-7.5°C in magnitude) with an average of 7.5 days during the period.

c) Temperature indices for Lagos

A decreasing trend was seen in maximum temperature with a magnitude of slope 0.04°C yearly while minimum temperature shows a positive trend and magnitude of 0.2°C per decade. Coldest night Tnn which represents the minimum value of daily minimum temperature (TN) during the 1991 – 2020 period shows no significant trend but indicates a decrease in the magnitude of (-0.02 yearly). The warmest night Tnx index also shows a significant positive trend at 95 percent and an average of 19.4°C during the period. Cold days TX10p indicates a decrease although no significant trend was observed. This is consistent with the occurrence of cold night events TN10p also indicating no significant trend but a slight decrease. CSDI which is when the minimum temperature (TN) remains below its 10th percentile shows a decrease (-0.64°C yearly) and a significant trend. There is clear evidence of trend for the warm spell duration index in Lagos during the period and a decrease in magnitude of (-0.39°C). The trends in the number of warms nights TN90p have increased significantly during the period of consideration with a yearly increase of 0.65°C. Coldest day TXn which is the minimum value of daily maximum temperature shows an increasing significant trend. Warmest day TXx index represents hottest days during the period 1991-2020 indicates a negative significant trend and a magnitude of (-0.03 per year). The significance of trends in TNn, TX10p, and TX90p indices is not as strong as those seen for the other indices for temperature extremes. TXx also shows a significant trend and decrease (-0.3°C) per decade. The warm days index TX90P shows no clear statistically significant trend in the occurrence of warm days, although a decrease magnitude of (-0.08 yearly) was found. On average, there were decreasing numbers of cool nights and days and increasing numbers of warm nights and days in the different climatic zones. These trends are significant.

d) Temperature indices for Makurdi

The trends of hot extreme temperature indices, the frequency of warm days (TX90p) are indicative of a clear trend towards more warm days over time. This trend may be associated with climate change, which is characterized by rising global temperatures. Increased warm days can have various consequences, including impacts on agriculture, water resources, and human health. Warm nights (TN90p) negative slope signifies a downward trend in the number of warm nights over the analysed period. Specifically, for each unit of time considered (30 year), the number of warm nights is decreasing by an average of 0.777 nights. The negative trend in warm nights may be linked to broader climate change patterns, particularly cooling trends or shifts in night-time temperature patterns. Changes in warm nights can have implications for ecosystems, agriculture, and human comfort. The significant increase in temperature observed in this study depicts increase in heat which makes the environment including the water body (River Benue) to be very hot during the day. During the night, some of the heats absorbed by the water body which serves as heat reservoir are gradually released through land and sea breeze. Therefore, Makurdi’s environs are extremely hot during the day and night. Thus, suggesting that the steady rise in temperature due to global warming. The implication of extreme hot days/warm nights on the inhabitants is that there may be high demand for energy, loss of food via post-harvest.

Similarly, cold days (TX10p) and cold nights (TN10p) showed significant negative trends. The frequency of cold days and cold nights decreased by -0.72 days and -0.56 nights per year. This implies that cold days and cold nights have decreased for the period under study. This is an indication of warming climate in the study area. Fewer cold days can have various impacts on ecosystems, agriculture, and human activities. It can affect the timing of plant growth, alter animal migration patterns, and influence energy demand for heating. Understanding the trend in cold days is essential for long-term climate planning and adaptation strategies. It can inform decisions related to infrastructure, agriculture, and energy resource management. For the warm spell durations, it suggests that the observed trend in the Warm Spell Duration Index is statistically significant at a significance level of 0.05. Longer and more frequent warm spells can have various impacts on ecosystems, agriculture, water resources, and human activities.

e) Temperature indices for Benin

The P-value of 0 indicates a highly significant downward trend in cold days, meaning this decrease is statistically significant and likely reflects a true climate shift. The negative slope of -0.662 suggests a steady annual reduction in cold days, likely due to overall warming. This could impact the ecosystem and agricultural practices, as fewer cold days could disrupt traditional seasonal patterns. For Warm Day, the P-value of 0.258 indicates that the increase in warm days is not statistically significant, suggesting the observed change might be due to natural variation rather than a consistent warming trend. The positive slope of 0.287, however, suggests a slight increase in warm days, though without sufficient significance to conclude a definite warming trend in daytime temperatures. For cold nights, a P-value of 0 and a negative slope of -0.54, there is a significant and steady decline in cold nights. This trend reflects warming night temperatures, which could indicate changes in nocturnal cooling patterns, potentially affecting human comfort, energy demand for cooling, and night-time ecosystem behaviour. For warm nights, the P-value of 0.001 shows a statistically significant increase in warm nights, with a slope of 0.617 indicating a marked annual increase in warm nights. This is particularly important as rising night time temperatures are often associated with reduced recovery times for people and crops after hot days, potentially affecting health and agriculture. For the warm spell duration index, a P-value of 0.997, this index shows no statistically significant change in the duration of warm spells, and the near-zero slope of 0.001 supports this lack of trend. It suggests that while individual warm nights may be increasing, prolonged warm spells aren't changing notably in length. For cold spell duration index, the P-value of 0 indicates a significant reduction in the length of cold spells, with a slope of -0.749 showing a notable annual decrease. This trend aligns with the broader pattern of warming and further underscores the reduction in the frequency and persistence of cold periods, with implications for seasonal variability and ecosystem resilience.

Overall, Benin City appears to be experiencing fewer cold days and nights, coupled with a notable increase in warm nights. However, changes in warm days and the duration of warm spells are not statistically significant. This temperature pattern suggests warming, especially at night, which could affect agriculture, human health, and ecosystems in the region.

f) Temperature indices for Port Harcourt

Warmest days TXx which signify the hottest days have been observed to slightly increase at 0.002°C per year although no statistically significant trends were observed within the period of 1991 to 2020. The warmest night shows a significant trend at $p \leq 0.05$ with an increase in the magnitude of 0.23°C per decade with an average number of is 24 days with the period. Non-statistically significant trends were observed the occurrences of warm days but a slight decrease of (-0.004°C per year) was present. Warm day shows a decrease at -0.04 per decade and averaged 10.4 days during the period. Warm nights show a highly significant trend at $p \leq 0.05$ with an increase of 0.6°C per year. Annual average of warm nights is 10.6 days and monthly maximums in June and August. The coldest day index presents a positively significant trend at $p \leq 0.05$ with a slope of 0.22°C per decade. This is an indication that the number of coldest days has increased and will therefore require increase energy/power for heating purposes. The coldest night index also presents a slight increase of 0.08°C per decade within the period although no statistically significant trends were observed at $p \leq 0.05$. Cold nights have also been on the decrease with an average 10.5 days within the period and a magnitude of (-0.61°C per year). Cold spell duration index CSDI which informs when the minimum temperature (TN) remains below its 10^{th} percentile presents a statistically significant decreasing trend at $p \leq 0.05$ and a magnitude of (-0.7 °C per year) and an average of 8.1 days. The average value for the Warm spell duration index WSDI is 6.3 days during the period, with a non-significant trend and a decrease of (-0.36 per year) within the period.

4.1.6.2 Precipitation indices

Six indices for precipitation were selected and calculated for each of the cities. The results have been summarized and tabulated in Tables 4.17 and 4.18. It has been observed that for the same indices, the result from different cities varies from each other. Significant trends are highlighted.

Table 4.17: List of Precipitation Indices

			Kano		Abuja		Lagos	
Indices	**Units**	**Indicator**	**Slope**	**P-Value**	**Slope**	**P-Value**	**Slope**	**P-Value**
Simple daily intensity index	mm/day	SDII	0.041	0.297	-0.043	0.223	0.024	0.164
Days with > 20mm rain	Days	R20MM	0.031	0.545	-0.028	0.819	0.089	0.32
Consecutive Dry Days	Days	CDD	1.899	0.003*	1.539	0.005*	-0.206	0.601
Consecutive wet Days	Days	CWD	-1.036	0.024*	-2.858	0.012*	-0.026	0.949
Rainfall on Extremely Wet Days	mm	R99P	5.299	0.071	2.414	0.204	4.327	0.033*
Total Precipitation	mm	PRCPTOT	-9.588	0.066	-20.03	0.015*	12.437	0.035*

* Statistically Significant

Table 4.18: List of Precipitation Indices

			Makurdi		Benin		Port/Harcourt	
Indices	**Units**	**Indicator**	**Slope**	**P-Value**	**Slope**	**P-Value**	**Slope**	**P-Value**
Simple daily intensity index	mm/day	SDII	-0.06	0.039*	-0.034	0.469	-0.025	0.661
Days with > 20mm rain	Days	R20MM	-0.133	0.277	-0.086	0.738	-0.37	0.251
Consecutive Dry Days	Days	CDD	0.988	0.135	-0.059	0.914	0.266	0.592
Consecutive wet Days	Days	CWD	-4.128	0*	-0.439	0.641	-0.448	0.631
Rainfall on Extremely Wet Days	mm	R99P	0.889	0.724	5.199	0.171	8.244	0.075
Total Precipitation	mm	PRCPTOT	-24.952	0.001*	-1.59	0.893	-6.346	0.666

* Statistically Significant

a) Precipitation Indices for Kano

At the annual scale, intensity indices, such as maximum consecutive 5-day precipitation amount (RX5day), annual total precipitation from very wet days (R95p), and annual total precipitation from extremely wet days (R99p) show no significant trend over Kano. Similarly, no significant trend is detected for maximum one-day precipitation amount (RX1day) and annual total precipitation (PRCPTOT). PRCPTOT described as the total accumulated precipitation (in mm) from "wet days" during the period 1991 to 2020 had no statistically significant trend at 95 percent confidence level but a reduction in rainfall of (-95mm) per decade is observed. The average value of PRCPTOT is 674.3mm. The decrease for the city of Kano is due to more frequent heavy and very heavy rainfall event. This intensification in the frequency of extreme rainfall events will result in high peak flow and then more damageable flood events in the high-water period. There is no clear indication of a significant trend at $p \leq 0.05$ for Rx1day and Rx5day but a slight increase of 8.7 mm and 11.1 mm were observed respectively. A decreasing trend is seen in Kano for R10mm with a magnitude of (-3.3mm per decade) and an average of 16 days during the period while R20 mm shows no significant trends. There has been very little increase of (0.4mm) in simple daily intensity index SDII but no significant trends were found. The Consecutive Dry Days CDD has a significantly positive trend with a magnitude of 18.99mm per decade and an average of 174 days within the period in Kano. Consecutive wet days CWD shows a significantly decreasing trend (-1.04mm per year) and an average of 37 days.

b) Precipitation Indices for Abuja

PRCPTOT, the total accumulated precipitation (mm) from “wet days” during the period 1991 to 2020 presents a negative significant trend and a decrease in rainfall of 200mm per decade. Wettest day RX1day and wettest 5 day Rx5day period both shows no significant although they indicate a slight increase during the period The simple daily intensity index SDII shows a decrease in magnitude during the period (-0.4mm) but no statistically significant trend was found at 95 percent. Days with 10mm rain (R10) averaged 40 days during the period and a magnitude of (-0.9 yearly) while days with 20mm rain (R20) averaged 7.9 days and a slight decrease of (-0.02mm yearly). A significant trend was also found to be present in R10mm. There is a positively significant trend in the Consecutive dry day’s index within the 1991-2020 period. CDD shows a magnitude of 15.4mm increase and averaged 111.2 days while CWD was found to decrease in magnitude (-28.6mm) and was positively significant during the period. Extremely wet days R99p shows some indication of an increase for R99P though no significant trends were observed within the 1991 to 2020 period.

c) Precipitation Indices for Lagos

Total precipitation PRCPTOT which is the total accumulated precipitation (mm) from “wet days” was found to have a positively significant trend at 95 percent confidence level with an average of 1444.18mm and a slope of 124.4mm of rainfall per decade. Wettest day Rx1day shows some indication of an increase, but with no significant trends at p (0.05) during the 1991 to 2020 period. The wettest 5-day period also shows no indication of significant trend. Simple daily intensity index SDII, days with 20mm and 10mm rain all shows some level of increase but no statistically significant trend was found. There is no significant trend in the consecutive dry day CDD and consecutive wet day indexes within the period, but an indication of decreases in the magnitude were observed. Only very wet and extremely wet day indices of all the precipitation indices for Lagos had a positively significant trend at 95 percent confidence level. Very wet days has an average of 327.73mm while extremely wet days has an average of 112.15mm during the period.

d) Precipitation Indices for Makurdi

From the precipitation extreme indices, the simple daily intensity index (SDII) showed significant negative trend. The trends of temperature indices suggest that Makurdi is becoming warmer in line with the global warming trend. Whereas, the precipitation extreme indices depict that rainfall in Makurdi for the period under study has decreased. The results of this study may have great implication on water resources and agriculture for which Makurdi is known for. The steady rise in temperature indices, depicting increase in hotness may likely cause water bodies such as lake, well, stream, and rivers to dry up while the decrease in precipitation may probably affect the amount of rainfall received in the area. This depicts that the region is trending towards a warmer and dryer climate which required urgent adaptation and mitigation strategies

The annual total precipitation (PRCPTOT) showed non-significant decreasing trend of -24.952. A decrease in total precipitation may contribute to increased drought risk, particularly if it results in prolonged dry spells and reduced water availability for various sectors. Consecutive wet day suggests that the observed trend is not statistically significant at a typical significance level of 0.05. An increase in consecutive wet days can have hydrological impacts, affecting soil moisture levels, flooding risks, and water resource management. However, the consecutive dry days (CDD) shows that the number of consecutive dry days is decreasing by an average of 4.128 days. The decreased consecutive dry days can have hydrological impacts, affecting groundwater recharge, soil moisture levels, and stream flow.

e) Precipitation Indices for Benin

At the annual scale, rainfall intensity indices, such as maximum consecutive 5-day precipitation amount (RX5day), annual total precipitation from very wet days (R95p), and annual total precipitation from extremely wet days (R99p) show no significant trend. Similarly, no significant trend was detected for days with 20mm and annual total precipitation (PRCPTOT). (PRCPTOT) described as the total accumulated precipitation (in mm) from "wet days" during the period had an increase in rainfall of (51.99mm) per decade observed and an average value of PRCPTOT is 1791mm. Increase in annual total precipitation for the city can aid in the increased floods observed within the city (Cirella *et al.*, 2019). Rainfall on extremely wet days R99p and wettest day also presents an increase of 5.2mm and 1.8mm respectively. This intensification in the frequency of extreme rainfall events will result in high peak flow and then more damageable flood events in the high-water period. There is no clear indication of a significant trend at $p \leq 0.05$ for wettest day Rx5day, simple daily intensity index, and R95p. Rainfall index (CDD) which is Consecutive Dry Days has a non-significantly trend although with a decrease of (-0.067 per year) and an average of 53.6 days within the period of 1991 to 2020 in Benin city. Consecutive wet days CWD also shows a non-significantly trend although a decrease of (-0.059mm per year) and an average of 78.1 days within the period.

f) Precipitation Indices for Port Harcourt

The P-value of 0.661 indicates no statistically significant trend in the simple daily intensity index, which measures the average intensity of daily rainfall. The very slight negative slope (-0.025) suggests a minimal reduction in average daily rainfall intensity, though this is likely due to natural variation rather than a notable trend. For days with > 20mm Rain, the P-value of 0.251 suggests that there is no statistically significant trend in the number of days with more than 20mm of rainfall. The slope of -0.37 implies a minor decrease in heavy rainfall days, but this trend is not statistically significant and might not reflect a consistent pattern. The P-value of 0.592 shows that there is no significant trend in the length of dry spells (consecutive dry days). The slight positive slope (0.266) indicates a possible increase in the duration of dry spells, though this change is not statistically significant and could be due to random fluctuations. For consecutive Wet Days, the P-value of 0.631 shows no significant trend in consecutive wet days. The negative slope of -0.448 suggests a small decrease in the length of wet spells, but, once again, this trend is not statistically significant, indicating no consistent change in the duration of consecutive rainy days. For rainfall on extremely wet days, a P-value of 0.075, this trend is on the edge of statistical significance, suggesting a potential increase in rainfall on extremely wet days. The positive slope (8.244) indicates an increase in precipitation on these days, possibly reflecting more intense rainfall events, though this trend is not conclusively significant. The P-value of 0.666 indicates no significant trend in total annual precipitation, with a negative slope of -6.346 suggesting a minor decrease in overall rainfall. However, this decrease is not statistically significant, meaning it likely does not represent a consistent trend. The results show that In Port Harcourt, the precipitation indices do not show strong, statistically significant trends in daily rainfall intensity, heavy rain days, or wet/dry spell durations. The only borderline trend is an increase in rainfall on extremely wet days, which might indicate more intense rainfall events. However, without stronger statistical support, it is difficult to confirm any consistent changes in the precipitation patterns for Port Harcourt City. This suggests that, overall, rainfall patterns remain relatively stable, with minor fluctuations likely due to natural variability rather than significant long-term shifts.

4.2 Discussion of Results

With rapid urbanization and increasing population growth, the possible challenges posed by the changes in climate in the future will make the cities more vulnerable to the impacts of climate change. A reliance on inter- connected and coordinated climate adaptation efforts could be the key in breaking the barriers to the implementation of future plans. The climate analogues are used to communicate and quantify the potential exposure of the populations to changes in climate conditions by locating areas/places with similar contemporary climate.

Despite the use of a highly optimistic climate change scenario (RCP 4.5), the climate conditions of the cities will change or shift to such a great extent that they will resemble more closely the conditions of another place entirely. This projected shifts shows consistency with the existing trends on changes in climate (Ramirez Villegas *et al.*, 2011), and a general shift towards the conditions in warmer, low-latitude regions (Bastin *et al.*, 2019). The extent and consistency of these patterns provide a stark reminder of the global scale of climate change threats and associated risks for human health (Chioma *et al.*, 2019; Das *et al.*, 2020).

The analogues of the Nigeria cities mostly shift to places within the neighbourhood of longitude (–10° to 20°). The similarity in cities under the different emission scenarios and periods are shown in Fig. 4.13-18. There are spatial differences in similarity between cities and their new regions but are mainly distributed in the in the south of Nigeria and within the West African tropics. In the 2030s periods (mean of 2021–2050), with climate policies and adaption plans put in place (RCP 4.5), places with similar temperature are mainly concentrated within west Africa while the RCP 8.5 are concentrated in central Africa. The best analogues of the cities are south of the corresponding, which indicates that the future temperature of the cities become warmer.

In the 2030s averages, all the cities have a representative analogue within Nigeria except for Kano City in the RCP8.5 and Benin City in the RCP 8.5 whether emissions continues or is mitigated throughout the 21st century. This indicates that changes will occur in the climate conditions for all the cities, thus increasing the vulnerability of these cities. Also, the climate conditions will become hundreds of kilometres away from the contemporary with an average of about 1,405km for the mitigated scenario and about 2,940km for the Unmitigated scenario. Thus, a different but not new temperature will be experienced in all the cities examined at varying levels except for Kano for both scenarios due to the lower similarity score. This implies that Kano's conditions will tend towards novelty.

Under the unmitigated scenario, the proportion of shifting cities varied consistently across the globe. For example, Benin future conditions remains in West Africa and consistent for both scenarios of 2050s and 2030s. These changes in climate for Benin would be equivalent to a shift approximately thousands of kilometres away in the 1971 – 2000 climate conditions. By 2050s, Makurdi's climate conditions will be more similar to the conditions of Jato in Kogi State RCP4.5 and Bali in Taraba State RCP8.5 in Nigeria. In the averages of 2050s, out of the 12 scenarios (6 cities and two future 30-year time periods), all six were successful in the identification of climate analogues (Although with a varying level of similarity). These highlighting the applicability of this method over Nigeria.

4.2.1 Implications for the Cities

Sustainable designs and actions to address the social, and environmental impact through urban planning and city management (Futcher *et al.*, 2017) are the best approaches in drawing lessons from analogues. In the capital city of Abuja for example, the best representation of the current and future conditions is located to the south of the city. The residents will experience new conditions mostly similar to the Northern Guinea savannah of Nigeria (Pabame *et al.,* 2018). The identified analogues for the city are on the same latitude; meaning that they would tend to have similar climate patterns (Lindberg *et al.,* 2014). This may be because they receive similar amounts of solar radiation throughout the year, thus resulting in comparable seasonal climate variations.

Given that there is a high inflow of residents into the capital city (Nwachukwu, 2014), proper planning and developmental control are needed to reduce the possible future impacts of climate change. (Kameni *et al.,* 2014), described the increasing impacts of climate events in the analogues, therefore conscious investments by the administrators of the city in technological solutions such as the use of permeable pavements to replace asphalt in road construction to mitigate urban heat (Anjos and Lopes, 2017) can be adopted by the city. Furthermore, social solutions such as the introduction of casual work attire in offices and the extension of office hours to cooler periods as adaptation to temperature-related hazards based on the conditions of the analogues can serve as adaptation. Although, according to (Gough *et al.,* 2019), adaptive capacity varies considerably among different places, cities like Abuja are expected to be able to cope to some extent with the impacts of climate change due to the already existing level of infrastructure and planning (Adama, 2020). In the immediate, environmentally friendly initiatives such as the use of vegetation to provide benefits to mitigate extreme heat (Scott *et al.,* 2016). Further analysis of the vulnerabilities will go a long way in exploring the different dimensions of adaptive capacities for future developmental plans.

Makurdi is another traditional city known for its ancient agricultural practices, especially for smallholder farmers and gardeners (Iortyom *et al.,* 2022) that shares similar characteristics in the current and future to the historical conditions of the Guinea savannah of Nigeria (A region characterized with the tropical wet and dry or savanna climate (Omonijo and Okogbue, 2014). Makurdi City can use this information to draw lessons from its analog such as the adoption of temperature-resistant varieties in their small-hold agricultural practices to facilitate benefits in terms of optimizing agricultural practices.

The southern region of Cote d'ivoire (A region that falls within the wet semi-equatorial climatic zone (Johnson *et al.,* 2023) represents the analogues of Benin City's in the current and future climate conditions. With the continuous occurrence of extreme weather events such as severe heat an in-depth understanding of its impacts on residents as a place most similar to the conditions of Benin City can provide a useful guide in climate policy formulations. Because Benin City is fast becoming a megacity, the integration of technological solutions in the housing sector such as improved open ridge ventilated thatched roofs may reduce the existing vulnerabilities to heat (Mandal *et al.,* 2021). Since construction in areas surrounding cities leads to expansion, building materials for future construction in Benin City such as light-coloured paints that would increase the reflectivity of sunlight, can also reduce the heat load of buildings (Francis and Jensen, 2017).

For the city of Lagos with a projected population of over 32 million by mid-twenty-first century (Healy *et al.,* 2020), the best representation of its condition is located within the same region in Lagos city for both scenarios of 2030s and 2050s. This is an indication that the residents of Lagos City will experience conditions of the wet tropical rain forest of Lagos. With the increasing population in the city of Lagos, the resuscitation and establishment of more urban green areas in strategic locations will help mitigate the effects of the changes in climate conditions on the residents. Although Lagos is fast developing with more modern infrastructures when compared to other cities (Abubakar and Doan, 2017), the planners will need to pay attention to the master plan by developing policies that will incorporate new housing initiatives to reduce flooding effects. Design strategies, such as shading, and exposure to the wind may improve the urban environments and residents' experience (Darbani *et al.,* 2023). The suburban areas surrounding the city of Lagos could be of advantage in future planning because of the possibility of integrating these designs from the inception of the development of these areas thus, reducing the vulnerability of the residents. An understanding of the climate conditions in Lagos could provide a unique opportunity to establish the necessary effective response strategies and climate-relevant action can be shared and transferred.

Port Harcourt, a high oil-producing city in the Niger-Delta region of Nigeria can consider how it’s analogue, the South-south region of Nigeria (A region with similar climate conditions) has taken actions toward combating their historical climate related challenges. Given that temperature-based index in Port Harcourt city are on the increase, deeper insights into the implications will be of great usefulness to policymakers and stakeholders in the designing of sustainable responses to climate-related hazards for the city. In planning for the future, the adoption of renewable energy technologies such as solar walls for the generation of power (Amuzu-Sefordzi *et al.,* 2018) and in the short term, housing designs for more ventilation of rooms can reduce urban heat (Akande, 2010). Therefore, reliance on shared knowledge and inter-connected climate adaptation efforts could be key in breaking the barriers to the implementation of plans.

4.3 Summary of Findings

The following are the summary of the findings of the study;

Changes in climate for the cities will threaten the occupant's quality of life and alter the cities' functioning because of the new climate-related issues associated. These new climate (temperature and precipitation) conditions will increase the vulnerability of the population and give them a feeling hundreds of Kilometres away from their current climate conditions. By translating the abstract statistical forecasts of future conditions into relatable experience with the past or present conditions, the nature of future local changes in average temperature and precipitation conditions can be described to the residents. This kind of communication is considered key in raising awareness in the public on the changes in climatic conditions.

In the 2030s averages, all the cities have a representative analogue within Nigeria except for Kano City in the RCP8.5 and Benin City in the RCP4.5 weather emissions continues or it is mitigated throughout the 21st century. The cities' climates will move or change so much that they more closely mirror the conditions of another location, even with the adoption of a very optimistic climate change scenario (RCP 4.5). The predicted changes are consistent with the current patterns of climate change (Ramirez Villegas *et al.,* 2011) and indicate a general tendency towards conditions more similar to those found in low-latitude, warmer locations (Bastin *et al.,* 2019). These patterns' scope and constancy serve as a sobering reminder of the challenges posed by climate change to human health on a worldwide scale (Chioma *et al.,* 2019; Das *et al.,* 2020). This indicates that changes will occur in the climate conditions for all the cities, thus increasing the vulnerability of these cities. Under the unmitigated scenario, the proportion of shifting cities varied consistently across the globe. For example, Benin future conditions remains in West Africa and consistent for both scenarios of 2050s and 2030s. In the averages of 2050s, out of the 12 scenarios (6 cities and two future 30-year time periods), all six were successful in the identification of climate analogues (Although with a varying level of similarity).

The number of warm days (TX90p) and nights (TN90p) have shown an increase with an average of 10 days each in the 30 years' period in the cities. The trends are statistically significant. The significance of TXn and TNn trend is not as strong as those seen for the other indices for temperature extremes (TNx and TXx). Coldest day TXn and night TNn indicated no statistically significant trend at 95 percent confidence level. Cold nights TN10p which is the number of cold nights presents significant downtrend for the cities at the average rate of (-3.3 °C/decade) and an average of 10 days for the period. The average number of cold days TX10P is 10.5 day during the period with an average magnitude of 3.7°C per decade. This is an indication that the number of coldest days has increased and will therefore require increase energy/power for heating purposes.

The annual total precipitation (PRCPTOT) showed non-significant decreasing trend for most of the cities. A decrease in total precipitation may contribute to increased drought risk, particularly if it results in prolonged dry spells and reduced water availability for various sectors. Consecutive wet day suggests that the observed trend is not statistically significant at a typical significance level of 0.05. An increase in consecutive wet days can have hydrological impacts, affecting soil moisture levels, flooding risks, and water resource management. However, the consecutive dry days (CDD) shows that the number of consecutive dry days is decreasing by an average of 4.128 days. The decreased consecutive dry days can have hydrological impacts, affecting groundwater recharge, soil moisture levels, and streamflow.

CHAPTER FIVE

5.1 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Major cities in Nigeria will experience changes and shifts in their climate conditions in the current and future periods under different climate scenarios. To achieve urban sustainability, conscious actions and designs to address the social, and environmental impacts of the changing climate through urban planning and city management are the best approaches in drawing lessons from places with similar conditions. Based on the analogues approach, the findings show that the six cities under study will experience changes in climate conditions for both the current and the future periods, which will be similar to the conditions identified in other places in the historical periods. The most similar places to the cities in the different scenarios and periods mostly shift to places within the neighbourhood of longitude (–10° to 20°) while their spatial distribution is mainly within West, Central, and Southern Africa. The best places identified as the analogues of the cities are generally south of the corresponding cities, thus indicating a north-south climate transect, and a warmer future. This is an indication of the potential increased vulnerability of the urban population to the changes in climate. In the capital city of Abuja for example, the best representation of the current and future temperature conditions is located to the south of the city. The residents will experience new temperature conditions mostly similar to the Northern Guinea savannah of Nigeria.

In the analysis of the climate extremes, there is a general increase in the number of positive trends associated with warmer temperature indices, while cooler temperature indices show decreasing trends. In general, the warm temperature indices show stronger warming trends and higher percentages of significant trends associated with warming.

Larger decreases in cold temperature indices, such as the cold spell duration index CSDI, are also apparent in the historical temperature dataset. This is an indication that indices related to cooling have decreased. Warmer minimum temperature indices show mixed trends with higher values noted at the coastal of Lagos and decreases moving in-land towards Abuja, and Kano. A similar pattern between inland and coastal is also present for the colder minimum temperature indices cold nights. However, there is some evidence of a general decreasing trend in rainfall events, with the cities showing less frequent >10-mm heavy precipitation days, consecutive wet days (CWD), and annual total precipitation. The implications of these trends on the local climate and environment can be significant and may have various impacts on water availability, pressure on already ageing infrastructure, energy consumption and the general livelihood of the urban residents.

5.2 Recommendations

Given the large and growing populations of these cities (2.4 percent to 3.6 percent annual increase) and their increasing level of vulnerability to climate change, specific development of adaptation policies such as the use of suitable heat-resistant materials for the construction of houses, the adoption of renewable energy technologies such as solar walls and in the short term, housing designs for more ventilation of rooms to reduce urban heat are adaptation measures drawn via targeted city to city interactions that could be incorporated into the planning processes for the city of Port Harcourt as seen in the Analogue.

The government of Lagos and the administrators should incorporate more parks and open spaces into the designs of new districts in the future in order to harness the lessons drawn from their analogues and at the same time adapt to the expected future changes. Although, Lagos is fast developing with more modern infrastructures when compared to other cities in Nigeria, the planners will need to pay attention to the master plan by developing policies that will incorporate new design considerations that helps in the reduction in energy consumption, increase shading, and improve exposure to wind

The study recommends the adoption of a comprehensive integrated approaches (via transfer and scale-up of local solutions), multidimensional resilience (adaptation and mitigation policies) which can be developed to address the challenges, while simultaneously improving liveability, and sustainability. Climatic analogues can advance policy, adaptation, and planning through informed decision making. Existing infrastructure may need to meet the demands of climates that not only are changing but, in some cases, will no longer exist.

The implication of the observed increasing warming may increase the risk of thermal discomfort and heat-related diseases. This may also increase the pressure, already high, on the power sector as the energy demand for cooling would increase. Thus, a crucial step in support of analogue predictions is to encourage educators, and social scientist to assess the extent to which analogue can help increase climate change engagement and awareness.

5.2.1 Recommendations on Policy Improvement

The greatest methods for learning from analogies when creating a sustainable city are those that involve designs and activities to address the social and environmental consequences through urban planning and city management. The findings of this study have significant implications for current policy processes, specifically regarding the development of locally based strategies and plans for adapting to specific urban settlements. Despite the fact that each of the cities will experience changes and shifts in their climate conditions in the current and future periods under different climate scenarios, the results still draws out the need for stakeholders such as the National Council on

Climate Change, Federal Ministry of Environment and Ministry of works and urban development to strength and create climate adaptation plans. Similarly, city-to-city interactions to draw lessons and form a foundation for informed decision-making to promote environmental sustainability and urban well-being can be adopted to improve existing strategies.

More importantly, the National Assembly in its legislative and oversight functions can ensure adequate climate financing to enable government institutions replicate similar studies with the aim of reducing climate change impacts through adaptation. Increasing the level of climate information dissemination by the government and civil society organizations could motivate preparation and improve the understanding of the expected changes.

5.2.2 Recommendations on Performance Improvement

Given the large and growing populations of these cities (2.4 percent to 3.6 percent annual increase) and that these urban areas are considered highly vulnerable to climate change, a reliance on inter-connected and in some cases aging infrastructure may be barriers to implementing coordinated climate adaptation efforts. The finding of the study provides policy driven information on the future conditions of the cities in the historical period to help the city managers and planners (Federal, State and Local government areas) visualize the future and facilitate efforts to establish specific strategies. By communicating the changes in climate (abstract projections and scientific forecast) into relatable personal experiences, the study provides proper understanding (explanation to stakeholders especially the National Emergency Management Agency NEMA, National Council for Climate Change and other policy makers) of the future impacts and possible opportunities.

5.2.3 Suggestions for Further Research

The study focused on the implications of future climate in term of temperature and precipitation on urban population. Other impacts of urban climate that were not considered in the study but relevant to the sustainable living of urban dwellers include humidity, land use characteristic, urban pattern of development amongst others. The incorporation of some of these other component could provide another approach to the implications of new or changing future urban climate on the population. Additional assessment on the analogue to examine how best to implement results of analogue to avoid mal-adaptation can be considered for improved urban planning to the expected future impacts of climate change.

5.3 Contribution to Knowledge

The study revealed that the climate of Nigerian cities in the current (average of 2030s) and future (average of 2050s) periods will be similar to the historical (1971 to 2000) climatic condition of another place on the globe based on the similarity scores. The new places with similar climate conditions are to the south of the corresponding cities (indicating warming) and within the neighbourhood of longitude (10°W to 20°E) in the tropics. The similarity scores in the mitigated scenario for the 2030s climate are; 0.81, 0.78, 0.77, 0.80, and 0.74, while the unmitigated scenarios are; 0.79, 0.64, 0.76, 0.68, 0.75 for Abuja, Lagos, Makurdi, Benin, and Port Harcourt respectively. This implies that the high similarity values of 0.81 and 0.79 for the city of Abuja presents a climatic condition most similar to Kuje and Teungo while the city of Kano with low similarity values of 0.64 and 0.68 presents a drastic change in climate conditions which is an indication climate novelty. Similarly, the results for similarity scores for the 2050s are; 0.8 0, 64, 0.74, 0.67, 0.71 if climate mitigation continues and 0.7, 0.61, 0.74, 0.69, 0.69 for the unmitigated scenario. Also, the city of Abuja in the 2030s has a 2.59 oC increase in temperature when compared to the historical period while the indices shows that the highest warming in minimum temperature is in Abuja and Kano. This significantly increasing trend in the hot and warm indices and the decreasing trends in the occurrence of cool days is an indication of warming for the cities. These are indications of increased exposure of the cities to climate impacts such as heatwaves, and for Kano city, water scarcity. The results implies that despite the use of a highly optimistic climate change scenario (RCP 4.5), the climate conditions of the cities will change or shift to such a great extent that they will resemble more closely the conditions of another place entirely. Drawing from the interaction between the cities and their analogues, the study advances the urban climate resilience literature by illuminating the future impacts of different climate scenarios on urban areas. To develop a climate sustainable city, a mix of infrastructure and behavioural change such as the incorporation of climate considerations into urban designs and policies to enhance human thermal comfort are required. The findings guides the understanding and application of the analogue approach and developed a more relate-able communication approach for climate change awareness by simplifying the complex abstracts and scientific projections of climate into personal experiences. The study further contributes to knowledge based on the following;

1. The study developed a more relate-able communication approach for the awareness on climate change by simplifying complex abstracts and scientific projections of climate into some more like a personal experience and thus, making it easy to improve stakeholder's knowledge.
2. The study shed light on the use of temperature and precipitation analogy for implications studies for future changes in climate and how they can be used to draw out lesson for place-to-place interactions.

3. Beyond communicating the exposures and possible impacts, the approach has shown that based on relevant set of variables, it can identify potential regions to serve as a guide for adjusting to potential climate risks and hazards by providing better policies and relevant actions in support of predictions from analogues.

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APPENDICES

Appendix A: CIMP5 Models Averaging (Equal Weights) and Analogues Codes

This method presupposes that each of your models are equally good representations of your underlying data

```
prediction_values <- prediction_values %>%
  mutate(equal_weight_pred = (lm_pred + ranger_pred + lightgbm_pred) / 3)
```

https://www.mm218.dev/posts/2021/01/model-averaging/

```
##= Set working directory
setwd("/home/ghislain/Documents/Ghislain-CIRAD/FRB_Mada/madaclim/climate/")
##= libraries
library(sp)
library(raster)
##= Variables
yr <- c("2050","2080") # For 2050, 2080
mod.ccafs <- c("ipsl_cm5a_lr","miroc_miroc5","ncc_noresm1_m") # For global climate models (GCMs): GISS-E2-R, HadGEM2-ES, CCSM4
## mod.ccafs <- c("csiro_access1_0","giss_e2_r","ipsl_cm5a_lr","miroc_miroc5","mohc_hadgem2_es", "ncar_ccsm4","ncc_noresm1_m")
mod <- c("ip","mc","no")
## mod <- c("ac","gs","ip","mc","he","cc","no")
rcp.ccafs <- c("4_5","8_5") # For representative concentration pathways (RCPs): RCP 4.5, RCP 8.5
rcp <- c("45","85")
var <- c("tmin","tmax","prec")

## Import
slope <- raster("/home/ghislain/Documents/Ghislain-CIRAD/FRB_Mada/madaclim/climate/slope_1km.tif")
values(aspect) <- asp.north

# stack
	tn <- paste("tmin_",1:12,".tif",sep="")
	tx <- paste("tmax_",1:12,".tif",sep="")
	pr <- paste("prec_",1:12,".tif",sep="")
	s <- stack(c(tn,tx,pr))
```

This is the source code of the package analogues.. The package was developed by CCAFS.

To install this package you can do:

```
library(devtools)
install_github("CIAT-DAPA/analogues")
```

If you do not have R package devtools installed then you will need to first run install.packages(devtoools) in your R console. You can also install devtools with the *install packages* option of R Studio.

You can use this package to calculate climatic similarity between a reference site and a prescribed area (e.g. the entire globe). This helps identifying locations with similar climates for, for instance, agricultural technology transfer or germplasm exchange. The following code should get you started (also see package examples):

```
library(analogues)
data(climstack)

#create parameters
params <- createParameters(x=-75.5, y=3.2, vars=c("prec","tmean"),weights=c(0.5,0.5),

ndivisions=c(12,12),growing.season=c(1,12),rotation="tmean",threshold=1,
                        env.data.ref=list(prec,tavg), env.data.targ=list(prec,tavg),
                        outfile="~/.",fname=NA,writefile=FALSE)

#calculate similarity
sim_out <- calc_similarity(params)

#now you can plot the result
plot(sim_out)

#or save the result
writeRaster(sim_out,"~/analogues_output.tif")
```

The above example computes similarity for a site in South America (lon=-75.5, lat=3.2) with respect to the entire world. Climate data is from WorldClim, aggregated to 2 degrees, and reflects current climatic conditions (1979-2000). The similarity is computed based on both precipitation and average temperature, using the 12 months of the year.

Appendix B: Values of the Climate Variable for the Analogues

Temperature Analogues of 2030s

Province	**Country**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	
North Province	Cameroon	22.8	24.9	26.8	26.8	25.4	24	23.3	23.1	23.2	24	24	23.4	24.31	Abuja
E/Province	Cameroon	23.1	23.7	24	24.3	24	23.4	22.4	22.6	23.4	23.3	23.5	23.1	23.4	Lagos
Siavonga	Zambia	25.7	25.1	25.3	24.9	22.5	20.3	20.2	22.6	26.5	29.4	27.9	26	24.7	Kano
Bamingui-Bangoran	Central Afri.	25.5	27	28.3	27.9	26.7	25.5	24.7	25	25	25.9	24.9	24.7	25.9	Makrudi
Ashanti Region	Ghana	25.2	26.1	26.4	26.3	25.9	24.7	23.7	23.3	24.1	24.8	25.3	25.2	25.08	Benin
S/W Region	Cameroon	24.9	25.9	26.3	26.1	25.6	24.8	23.9	23.6	24.3	24.8	25.2	24.9	25.03	Port/H
Logone Oriental	Chad	23.9	26.3	28.4	28.1	26.8	25.1	24.1	23.9	24.2	25.1	25	24	25.41	Abuja
Comoe	Côte d'Ivoire	26.3	27.1	27.3	27.3	26.6	25.3	24.5	24	24.6	25.6	26.4	26.3	25.94	Lagos
Mashonaland	Zinbabwe	25.2	24.7	25	24.4	21.9	19.6	19.5	22	26	29.1	27.7	25.6	24.23	Kano
Bamingui-Bangoran	Central Afri.	25.1	26.7	27.8	27.3	26.2	24.9	24.1	24.3	24.4	25.2	24.3	24.1	25.37	Makurdi
Ugie Provice	Angola	24.9	25.4	25.8	25.8	25.4	24	22.8	22.5	23.3	24.2	24.4	24.7	24.43	Benin
Lengupa Province	Colombia	26.9	26.8	26.8	25.9	26	24.9	24.4	24.5	25.2	25.7	26.2	25.7	25.75	Port/H

Temperature Analogues of 2050s

1	2	3	4	5	6	7	8	9	10	11	12	AVE	Point.ID	Temp	Value	State	Country
23.5	25.2	27.2	27.1	26	24.3	23.6	23.4	23.5	24.4	24.1	23.1	24.6	Abuja	4.5ens	0.81	Adamawa	Nigeria
22.4	24.5	26.1	25.6	24.5	23	22.2	22	22.3	23.1	23.2	22.5	23.5	Abuja	8.5ens	0.84	Ngaoundaye	CAR
26.7	26.8	26.7	26.1	25.3	24.5	24	24.3	25	25.7	26.2	26.1	25.6	Lagos	4.5ens	0.8	Aracaju	Brazil
25.4	25.8	25.5	24.3	23.5	23.1	22.5	22.7	23.2	24.1	24.4	24.6	24.1	Lagos	8.5ens	0.79	Soroti	Uganda
24.1	25.9	27.5	27	26	24.6	23.8	23.8	24	24.7	24.7	24.1	25	Makurdi	4.5ens	0.76	Paoua	CAR
23.7	25.5	26.8	26.3	25.4	24	23.2	23.2	23.4	24.1	24.3	23.8	24.5	Makurdi	8.5ens	0.76	Bocaranga	CAR
24.5	25.5	25.8	25.6	25.2	24.4	23.6	23.3	23.8	24.3	24.8	24.5	24.6	Port/H	4.5ens	0.81	Mundemba	Cameroon
24.4	24.4	24.3	23.5	23	22.5	22	22.2	22.9	23.3	23.5	23.6	23.3	Port/H	8.5ens	0.8	Budiope	Uganda
25	26.1	26.3	26.1	25.7	24.6	23.6	23.2	24.1	24.7	25.3	25	25	Benin	4.5ens	0.81	Kwahu Easr	Ghana
24.6	25.6	25.8	25.7	25.2	24.1	23.2	22.8	23.8	24.3	24.9	24.6	24.6	Benin	8.5ens	0.78	Kwahu South	Ghana
24.2	23.7	23.8	23.3	20.9	18.8	18.7	21	24.8	27.6	26.3	24.5	23.1	Kano	4.5ens	0.65	Chikankanta	Zambia
23.6	23.6	23.2	22.6	20.5	18.4	18.3	20.4	23.8	26.7	26.1	24.2	22.6	Kano	8.5ens	0.63	Petauke	Zambia

Precipitation Analogues of 2030s

City	State/ Province	Country	1	2	3	4	5	6	7	8	9	10	11	12	X
Doufelgou	Kara Region	Togo	1	7	40	83	142	168	224	247	260	112	14	4	Abuja
Lagos	Lagos	Nigeria	24	39	90	141	245	373	251	92	171	167	64	18	Lagos
Kano	Kano	Nigeria	0	0	1	7	37	94	177	234	98	11	0	0	Kano
Makurdi	Benue	Nigeria	5	7	33	101	189	189	185	214	249	147	11	1	Makurdi
Benin	Edo	Nigeria	9	45	109	166	202	272	338	250	342	237	64	22	Benin
P/Harcout	Rivers	Nigeria	29	67	136	187	235	313	377	330	394	287	110	32	Port/H
Zango	Kuje	Nigeria	3	9	31	83	157	173	220	256	274	131	10	1	Abuja
Obanikoro	Lagos	Nigeria	24	39	90	141	245	373	251	92	171	167	64	18	Lagos
Guma	Kano	Nigeria	0	0	1	6	31	84	169	220	91	10	0	0	Kano
Fuamah	Benue	Nigeria	4	5	31	91	177	187	183	214	244	147	10	1	Makurdi
Oredo	Edo	Nigeria	9	43	109	161	198	262	321	239	333	228	60	21	Benin
Dambatta	Bong	Liberia	21	66	136	189	191	284	296	321	419	277	123	51	Port/H

Precipitation Analogues of 2050s

1	2	3	4	5	6	7	8	9	10	11	12		Point.ID	Values	City	State	Country
2	11	50	92	140	179	229	245	259	128	17	6	113.17	Abuja	0.88	Kara	Kara	Togo
9	12	35	72	187	176	185	250	261	116	21	4	110.67	Abuja	0.89	Tao Bamrung	Uttaradit	Thailand
24	39	90	141	245	373	251	92	171	167	64	18	139.58	Lagos	0.81	Lagos	Lagos	Nigeria
24	39	90	141	245	373	251	92	171	167	64	18	139.58	Lagos	0.78	Lagos	Lagos	Nigeria
1	3	31	91	157	189	198	220	246	144	11	2	107.75	Makurdi	0.81	Bali		Nigeria
5	7	33	101	189	189	185	214	249	147	11	1	110.92	Makurdi	0.83	Makurdi	Benue	Nigeria
29	67	136	187	235	313	377	330	394	287	110	32	208.08	Port/H	0.75	Umuehere	Rivers	Nigeria
29	67	136	187	235	313	377	330	394	287	110	32	208.08	Port/H	0.77	Umuehere	Rivers	Nigeria
9	45	109	166	202	272	338	250	342	237	64	22	171.33	Benin City	0.78	Etet	Edo	Nigeria
9	45	109	166	202	272	338	250	342	237	64	22	171.33	Benin City	0.75	Etet	Edo	Nigeria
0	0	1	7	35	91	175	231	96	10	0	0	53.83	Kano	0.86	Gabassawa	Kano	Nigeria
0	0	1	7	36	92	176	231	97	11	0	0	54.25	Kano	0.87	Dambatta	Kano	Nigeria