Research

Evidence from temperature analog for traditional and economic cities in Nigeria: implications for sustainable city-related actions

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Abstract

Responding to the threats of climate change by cities requires taking relevant actions that will communicate future conditions in reliable and effective manner for sustainable and transformational climate actions. We used the analog approach to assess the geographical shifts and changes in average temperature conditions for six traditional and economic cities under different climate scenarios (Mitigated and Unmitigated scenarios). We calculated the similarity in temperature between each pixel for the current (2021–2050) and future (2041–2070) conditions of the cities, with every pixel globally in the historical (1971–200) period. Our analysis revealed that; (1) the temperature of the cities in the current and future periods will be similar to conditions of another place on the globe during the historical period; (2) Kano city will experience even more drastic changes because of the low level of similarity to other places; (3) the new places found with similar temperature conditions are generally to the south of the corresponding cities thus indicating warming. The overall results show that the analogues of the cities are within the domain of the global tropical zone which occurs around the equator. Drawing from the interaction between cities and their analogues, we highlighted sustainable city related actions such as the incorporation of urban designs and policies to enhance human thermal comfort as adaptation and solution strategies. While future research might apply qualitative studies and additional data to support the analog results, our findings can guide the understanding and application of the analog approach into environmental issues in Nigeria and other West African countries in accordance to sustainable city goals (SDG 11).

Keywords Analog · Climate action · Nigeria · Sustainable cities · Temperature · West Africa

1 Introduction

Global warming leading to climate change is a major concern in global environmental change, and a barrier to achieving sustainable development [1]. The global effects of warming are clearer as scientific evidence continues to show that climate conditions are changing and the people, the planet, and their survival are threatened [1]. Across the world, a series of recent studies on urbanization have indicate that the outcomes of urban transformation and

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Discover

dynamics stemming from factors such as land-use land-cover alterations, expansion of built-up areas, and population growth result in a rise in urban temperature. For example, in the city of Tehran, it was reported that a positive correlation exits between major air pollutants and urban land surface temperature [2]. In Germany, prevailing atmospheric pollutants such as Nitrous dioxide, Sulphur dioxide were linked to mutual complex factors of increasing population density, land use and urban heat island [3, 4]. Similarly, in Cyprus, transformation of land-use land cover has been implicated to be responsible for increased urban land surface temperature [5]. These interactions due to intense urbanization amounts to significant consequences which includes heightened air and noise pollution, health challenges and increased pressure on urban infrastructure among others thus contributing to global warming and threat to the sustainability and safety of cities in the context of sustainable city goals (SDG 11) [2, 5, 6].

Critical global climate features such as temperature are projected to be a minimum of 1 °C warmer than the 1850–1900 average (preindustrial) levels, with 2015–2022 being the warmest [7]. Across the globe, each continent is confronted with harsh and uncertain climate conditions. In Europe, temperature has increased more than the global average (1.3 °C) [8] while in Asia, the total number of deaths due to short-term exposure to temperature is 7.62% [9]. In Africa, surface temperature is observed to have increased by at least 0.5 °C in the last 50 to 100 years, and the maximum temperature rises more quickly than the minimum temperature [7]. The West African sub region is one of the most vulnerable regions to climate change and variability, a situation further aggravated by low adaptive capacity. Higher temperatures have led to a high rate of evaporation and very dry conditions in some areas leading to an increase in the occurrence of severe weather events (drought, thermal discomfort and agricultural loss etc.). Adaptation policies and actions driven by the application of analogues will be effective if they are based on the best knowledge concerning the present and future climate conditions [10]. In the future, Nigeria's temperature is projected to increase by 0.0–4.0 °C in the representation concentration pathway RCP8.5 climate scenario and by 2.5–4.0 °C in the RCP4.5 scenarios. While these projections are critical for climate change response, planning of adaptation and mitigation of greenhouse gases, scientific projections are usually of limited meaning because they are not tied to reflect critical socioeconomic impacts [11].

To a large extent, critical sectors of human existence mostly in cities are still sensitive, exposed and vulnerable to the severe impacts of the changing climate across the globe with little or no interpretation of the potential impacts [12]. These impacts make cities even more vulnerable because cities are areas with a concentration of human wealth and people [13]. 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 [14, 15]. The primary consequences of these are the consistent rise in temperature in urban atmosphere [16]. In Kano city, there was an upward change in microclimate temperature of nearly 2 °C in 2018 compared to 1980. These changes witnessed in urban form and climate are attributed to rapid urban expansion and poor planning systems [15]. Abuja city in recent times has experienced an increase in both surface and atmospheric temperatures. 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 [17]. Similar prolong urban transformation in Lagos due to poor urban governance, poorly maintained critical infrastructure and coastal location of Lagos city has further compounds climate vulnerability of the city to flooding, sea level rise, rainfall intensity and high temperature [18]. As with other cities, Port Harcourt, the industrial hub of the Niger Delta region of Nigeria is also faced with its own urbanization challenges, largely due to lack of urban planning and population. The oil exploration activities have further contributed to health, environmental and socio-economic problems [19]. Today, the temperature in Port Harcourt city has increased drastically resulting to high level of heat wave. These transformation situations in terms of built-up and population density, is also true for emerging cities such as Makurdi and Benin, which gives insights into the enormous challenges faced by traditional and economic cities in West Africa and their preparedness to cope with local and global climate change risks and hazards [20]. With the increased projection of urban dwellers by 1.5 times in 2045 [21], the vulnerability of cities and its dwellers will certainly continue to increase. While stakeholders in city affairs argue for the need to plan for city growth through relevant infrastructures, the impacts of climate change which threatens cities and increases their functional rigidity should not be undermined in the planning [22].

Despite these concerns, most cities are yet to implement or have climate response plans that are geared toward addressing the possible impacts of climate change [23]. This contextual gap has been attributed to the limited understanding of the underlying science and complex data [24]. Relevant scientific concerns in different sectors also includes; what are the expected severe impacts of climate change in the future, how to characterize it, how vulnerable people understand and respond to it, and how to improve stakeholder engagement for critical actions. [24–26]. Translating and communicating some of these concerns in terms of personal experiences may help overcome some barriers to public recognition of the risks of climate change [27]. With so many uncertainties about future climate change impacts [28],

an understanding of the impacts in a relatable manner could be the key to raising public awareness and increasing the knowledge of the expected changes. Thus, investigations of climate variables focusing on future conditions and their interpretations into historical relatable experiences are essential to improve the understanding of potential threats and possible planning opportunities [29]. Several global warming projections have shown that there will be severe impacts of climate change on global communities [30]. For example, rapid urbanization without efforts to increase resilience will expose cities around the globe to enormous risks. For instance, [31] studied the exposure and vulnerability of 1860 cities and urban areas and concluded that almost 58% of the cities were highly exposed. In another study, it was shown that climate change has caused mega-drought in some Western states in America recording the driest stretch in at least 1200 years [32]. In West Africa, climate variability exacerbates the incidence of malaria from 24% during the dry season to 76% during the rainy season in Nigeria [33]. 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.

The climate-analog characterization is a statistical technique that quantifies the similarity of a location's climate relative to the climate of another place [26]. The analog approach is based on the premise that human systems will probably conduct activities as they have done in the recent times and be influenced by similar conditions and processes [34]. Literature has shown the use of spatial–temporal analysis of analogues, whereby past and present experience and response to climatic variability are examined to uncover knowledge about vulnerabilities and adaptive response [34]. The identification of analog conditions can then form the basis for undertaking relevant actions. Once analogue sites are identified, information gathered from field studies or databases can be used and compared to develop further studies or propose high-potential adaptation pathways. Aside the comparison potentials, analog approach can facilitate exchange of knowledge, validation of computational models, testing of new technologies or techniques and learning from history. Although, considerable uncertainties remains regarding input projections data in the analog approach, these uncertainties can prevent the accurate assessment of what the future may look like and how it may shape cities outlook. Region specific tweaks, validation processes and additional data may be needed to support the results. Despite the limitations, analog has been extensively used and scientifically recommended. For the late twenty first century, [27] adopted analog approach to find contemporary climate of selected North American urban areas, [26] used the method for the potential intensification of global crop production, and [13] used the method to communicate the implications of climate change in European cities. However, the application of analogs as an approach has not been notably applied in the West African sub-region (Nigeria) where climate change has been projected to impact every sector.

Of scientific and contextual importance is the question of where the future or current temperature conditions of a city can be found in the historical period. An effective way to determine such similar places is to make use of projected climate data from earth system models in different periods and scenarios through the climate analog approach [27]. As a form of climate analog, temperature analog is a technique that matches the proposed future or current temperature of a location of interest with the historical conditions experienced in another location [26]. The temperature analog approach is a support tool for the interpretations of the results of model outputs and the recommendations of policies [35]. While the temperature analog approach would be effective for conveying climate change information [36], it also provides an opportunity for comparison between past and future temperature scenarios [37]. Thus, temperature analogs serve as a veritable location of reference for future responses to climate change. Temperature plays a crucial role in cities, as it influences human comfort and drives energy consumptions [38]. Understanding the importance is critical for effective urban planning, and the general well-being of urban populations. Thus, climate-responsive policies and strategies can help cities adapt to temperature variations and create more resilient, and sustainable environments [38].

In this study, we investigated and provided the analog evidence of temperature for six selected traditional and economic cities in Nigeria from multi-ensembles models and projections. We answered the question of where are the places with similar temperature conditions in the historical period to the projected future conditions. With this, we provided insights into the potential use of the analog method as a decision-support approach for the identification of possible responses (adaptation plans) to tackle the temperature related city challenges in view of planning and enhancing city adaptations in Nigeria. This is based on the assumption that one city's future conditions may be similar to the past or current conditions of a different place [27]. The significance of this study lies in its potential to provide an understanding of the knowledge of urban climate management through the utilization of analog methodology. It also demonstrates insights and strategies for stakeholders to address the current and future temperature challenges faced by cities. This paper is divided into four sections, the next section presents the materials and methods; section three presents the results and discussions; section four presents the study conclusion.

2 Materials and method

2.1 Study area—Nigeria

The study country is Nigeria in West Africa. Nigeria is located between Latitude: $4^0 15'$–$13^0 55'$N and Longitude: $2^0 40'$–$14^0 45'$E. It shares borders with Chad, Chad Basin and Cameroon to the east, Benin Republic to the west, and Niger to the north Fig. 1a. The country's national population was recently estimated to be over 200 million people with approximately 52% urban dwellers [39]. The main seasons are the rainy and dry seasons with variations from north to south. Rainfall is usually high, varying from over 2000 mm in the south to 500 mm in the north [40] while daily maximum temperature ranges from 30 °C to 45 °C. Nigeria has six agro ecological zones which are defined by temperature and rainfall distribution [41]. (Fig. 1b) shows the Sahel Savannah which is characterized by desertification, moving sand dunes and the silting of water bodies; Sudan Savannah with high threat to vegetation due to deforestation for fuelwood; Guinea Savannah which is the major food basket for Nigeria and characterized by a mix of trees and grassland; Rain forest region in the south which is characterized by a high human population density and subjected to logging and rapid urbanization; Fresh water swamp and Coastal/Mangrove forest which are characterized by fresh water vegetation and farmlands Zone [42]. The six selected cities were drawn from four of the major agro-ecological zones in Nigeria excluding Sahel savannah and fresh water.

2.2 Choice and description of selected cities

The cities namely; Kano, Abuja, Makurdi, Benin, Lagos, and Port Harcourt have established populations of well over three million people and are considered as mega and major cities in Nigeria [43]. These cities are industrial and administrative centers that drives the economic growth of Nigeria and houses the highest population and decisions makers of their respective states. 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 [43]. They represent regional hubs that attract dwellers from both within and outside their geopolitical regions based on their economic activities.
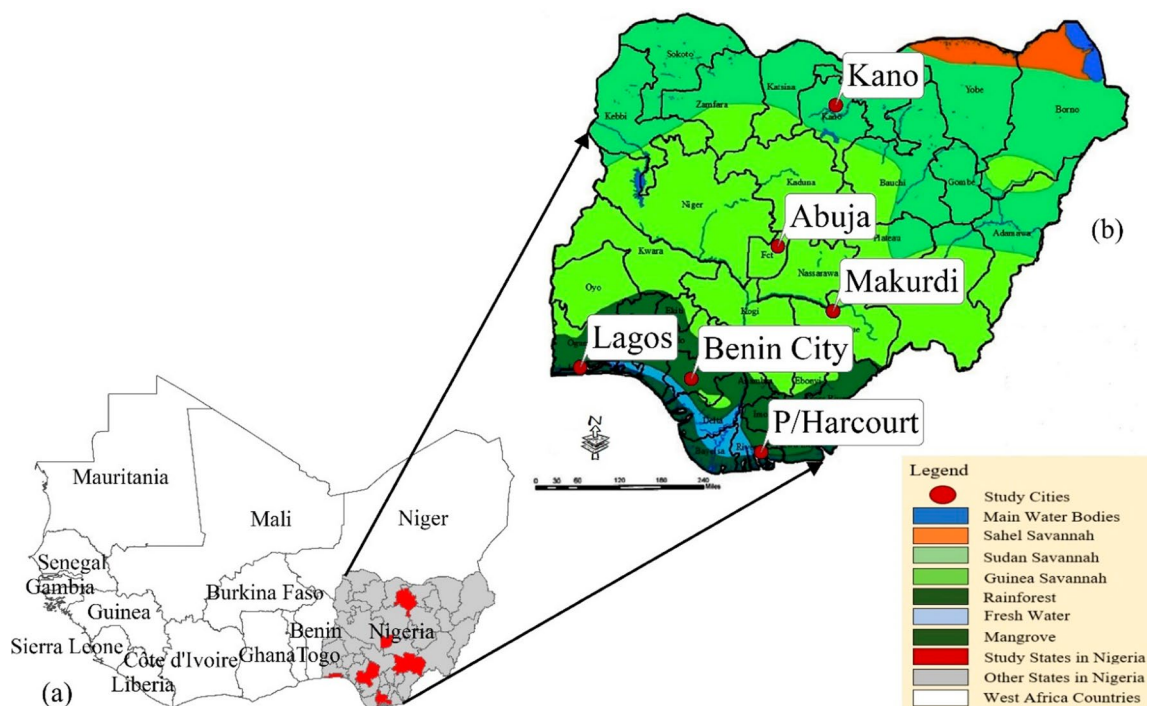

Fig. 1 Study area showing **a** Nigeria Extract from West Africa, **b** Ecological Zones of Nigeria and the Study Cities. (Adapted from [42])

2.2.1 Kano city

Kano City is a precolonial ancient city in the Sudan savannah of Nigeria. It is located in Northern Nigeria between 11°50′ N—12°07′ N and 8°22′ E and 8°47′ E [15]. In the 2006 census of Nigeria, Kano's population was over 9 million, making it one of the most populous cities in Nigeria with a great political influence [44]. Kano city owes its existence to the trans-Saharan trade and the agricultural abundance of the surrounding region [45]. Kano Metropolitan's growth rate currently stands at 3.9%, this is one of the highest in Nigeria. The city's growth is above the Nigeria average of 3.2% [46]. The city's climate is characterized as a tropical wet and dry savannah, coded 'Aw' according to Koppen's climatic classification and the yearly mean temperature is between 26 °C and 28 °C for the study period [47].

2.2.2 Abuja city

Abuja is the capital of Nigeria with a growing population of over 3.5 million people and one of the most populous cities in Nigeria [48]. The average temperature of the city is 25.78 °C in the study period. It is located in the Guinea Savannah [49] between 7°20′ and 9°15′ North and 6°45′ and 7°39′ East with the Gwari tribe as the original habitant. It occupies an area of about 8,000 square kilometers and was built in the late 1980s before it became the capital of Nigeria in 1991 making it the fastest-growing city in Nigeria [50]. Abuja is under the Köppen climate classification which features a tropical wet and dry climate [51].

2.2.3 Makurdi city

Makurdi City is the state capital of Benue State, the food basket of Nigeria with a population of approximately 4.3 million people in the 2006 census [52]. It is located in the Guinea savannah of Nigeria on 7° 43′ 58.8" N and 8° 32′ 20.76" E [53]. The average temperature is 27.19 °C during the study period. It is a traditionally food-producing region with most of the surrounding towns and villages engaged in agricultural activities. Classified as a major city [43], Makurdi city is situated in the Benue Valley in the middle belt region and traversed by the river Benue.

2.2.4 Benin city

Benin City is the capital of Edo State, a precolonial ancient city [54] located in the humid tropical rainforest belt of Nigeria. It lies between 6°23.055′ N and 6°27.339′ N and 05°36.0018′ E to 05°44.130′ E [55] with a projected population of over 4 million people [56]. Regarded as one of the most populous cities in the Southern part of Nigeria, Benin is a traditional city with history of artifice trade thus, an enviable city for tourist attraction. The natural vegetation of the city consists of tropical rainforests and lowlands known for rubber and palm oil cultivation [57].

2.2.5 Lagos city

Lagos is a mega coastal city located in the southwestern region with a border to the Atlantic coastline. It is located in the tropical rainforest zone of Nigeria [58] between latitude: 6° 23′ – 6°41′N, and longitude 2°42′ – 3°42′E [59]. It is a pre-colonial city with a land mass of 3,577 km^2 and characterized by landform features such as wetlands, islands, beaches and low-lying tidal with flat terrain [60]. It is regarded as the commercial hub of West Africa due to the heavy activities of the sea port and an urban population of over 9 million inhabitants [61]. Average temperature condition during the study period is 27.09 °C.

2.2.6 Port Harcourt city

Port Harcourt metropolis is a major oil-producing city in the Niger Delta region of Nigeria located on Latitude 4°55′N, and 6°55′N Longitude 6°55′E and 7°05′E [54]. It is the capital of Rivers State with a population estimated to be over 2 million in 2016 [62]. Port Harcourt city's average temperature within the study period is 26.26 °C and it is characterized

ecologically by freshwater swamp forests, lowland rain forests, and mangrove forests [63]. It occupies about 397 square kilometers of land [54] and serves as a repository of national resources of significant economic value to Nigeria.

2.3 Dataset and processing

Temperature as described by [64] is part of the essential climate variable that can have considerable implications on the urban population. Although other climate variables are important and play a vital role in urban environmental conditions, this study only focused on temperature analogs. The analysis of temperature analog requires two sets of data; Historical temperature data which represents the reference conditions for which the analog is determined (mean conditions for 1971 to 2000) and projected data which represents the current conditions (Mean conditions for 2021 to 2050) and future conditions (mean conditions for 2041 to 2070) under the RCP4.5 and RCP8.5.

2.3.1 Historical data

For the historical temperature data, we used monthly average temperature for the periods of 1971 to 2000 obtained from WorldClim (https://www.worldclim.org/) (Fig. 2, Box 1). WorldClim is a database of global climate data widely used for spatial climate modeling and mapping [65]. It has been widely used for climate studies due to the availability, global coverage, high-resolution, and the gridded nature of the dataset. It has the same spatial resolution with the climate projected dataset thus making computation easier. It is a spatially interpolated monthly climate data for global land areas with a resolution of 5 min. The choice of the historical temperature reference period of 1971 to 2000 was informed by data availability and the need to provide a comparative baseline for current and future climate events.

2.3.2 Current and future data

Downscaled and bias-corrected temperature data for the current period of 2021–2050 (2030s averages) and future period of 2041–2070 (2050s averages) at 5-min resolution were obtained from the international agricultural research program on climate change, agriculture, and food security CCAFS (http://www.ccafs-climate.org/) (Fig. 2, Box 2). The suitability, public accessibility, bias correction and wide usage of the data informed the adoption for the study. The CCAFS projected dataset
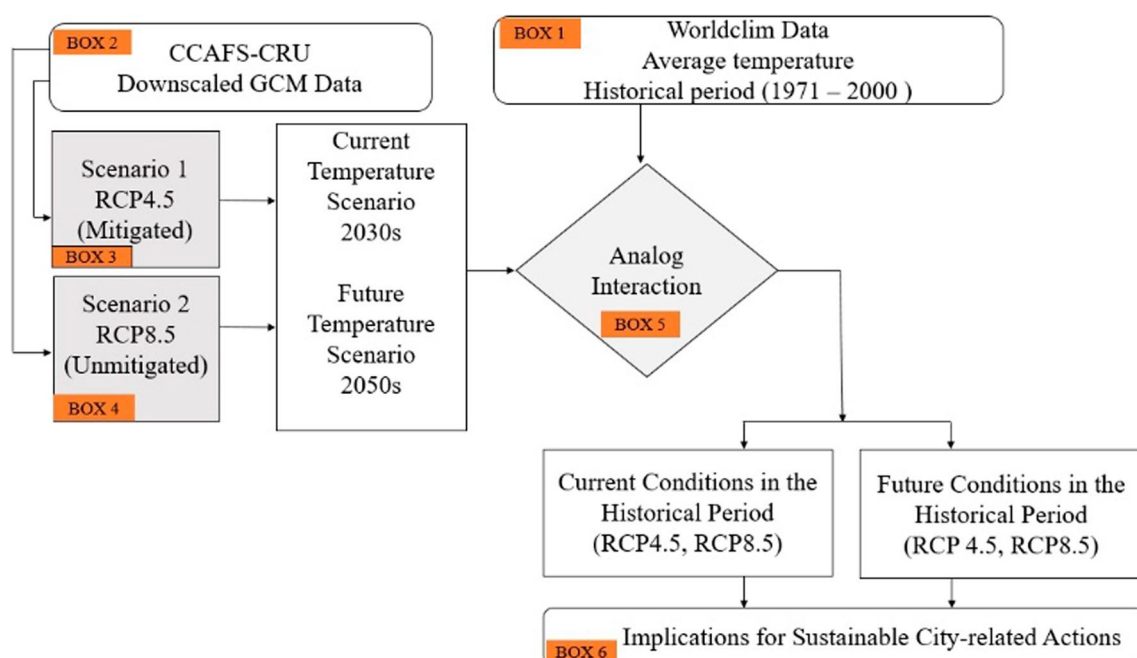

Fig. 2 Work Flow of the Research

was developed by applying the delta method: a downscaling method for climate model [66]. The pre-processed data based on the method has already been proven to be robust in correcting mean climate conditions in different regions [67]. The delta method was applied to 3 Global Climate Models from the Coupled Model Inter-comparison Project Phase 5 (CMIP5); CSIRO-Mk3, MIROC-ESM, and HadGEM2 [7]. We used outputs 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 [68], and RCP8.5, an unmitigated scenario, where greenhouse gases continue to rise [69]. The results are based on an ensemble average of the 3 models while the choice of models is based on good performance over Nigeria [40]. Extensive applications of the CCAFS high-resolution datasets include climate impact assessments on agricultural productivity, environmental studies, and climate impacts on biodiversity conservation [66].

3 Method

The specific objectives of the study were addressed through the workflow showing the various research methodology components (Fig. 2). The climate analog of temperature is a statistical approach that analyses and quantifies the similarities between locations. These makes use of specified locations, variables and climate scenarios as introduced by the IPCC [26]. It can be used for any variable for which data are available for several time steps of interest. In this study, we match any location globally in the historical period with other locations in the current and future periods that share similar temperature conditions using the analog approach. To investigate our cities' temperatures, we describe the analog approach as linking the current and future average temperature of the cities to the historical temperature of another location.

3.1 Data extraction

For each of the cities, we extracted mean monthly projected temperature conditions for the 2030s and 2050s periods for each of the temperature scenarios (3 models and 2 RCPs). Data from 3 earth system models (Box 2), forced by two Representative concentration pathways RCP4.5 (mitigated scenario Fig. 2, Box 3) and RCP8.5 (unmitigated scenario Fig. 2, Box 4) were utilized. The model output was averaged for each of the scenarios to form an ensemble mean projections for the RCPs in each of the periods considered. In total, the datasets comprise outputs for 4 future scenarios (2 scenarios multiplied by the two periods).

3.1.1 Analysis of temperature analog

We adapted the 'CCAFS dissimilarity' climate analog method and R scripts by [26] which is similar to that described by [70] and [71] to determine the temperature analog for these cities globally. In the CCAFS dissimilarity measure (Analog interactions Box 5), 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 [26]. The analogs 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 [71]. Euclidean distances (i.e., dissimilarity indices) were estimated for the current period (2030s averages) and the future period (2050s averages) locations based on the coordinates of the cities. The analysis was calculated using the analogues package in R [26]. 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 analog has the highest pixel value within the analog temperature surface (See supplementary file for temperature similarity surface). For the current and future conditions, an analog similarity score or value of 1 indicates a perfect match, > 0.5 denotes an increasing level of similarity, < 0.5 denotes a decreasing level similarity while 0 indicates no similarity (meaning complete Novelty for the temperature condition). It is important to acknowledge the different limitations of the analog approach given the fact that the results are sensitive to the threshold selections to discern good, poor, or no analogs [26]. To estimate the distance of the cities to their respective analogs, the distance tool in ArcGIS was used to analyze the straight-line distance. Based on knowledge transfer involving insights from the analogs and literature on sustainable and smart cities, we identified and proposed relevant actions for each of the selected cities in Nigeria (Fig. 2, Box 6).

4 Results and discussion

This section presents the overview and the similarity surfaces of temperature analogs for the six selected traditional and economic cities. The individual temperature similarity surfaces for each city are presented in the supplementary file (Fig (SF1—6)). The results and discussion are presented based on the two scenarios.

4.1 Overview of the current and future temperature shifts

Figure 3&4 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 respectively under the RCP4.5 and 8.5 scenarios.

   The arrows from both Figs. 3 and 4 show the direction of the city shifts to temperature conditions most similar to their current (2030s) and future (2050) conditions in the historical period of 1971–2000. Locations in green represent the RCP4.5 mitigated scenarios while red represents RCP8.5 unmitigated scenarios.

4.2 Cities—current and future temperature similarity

Table 1 supporting Figs. 3 and 4 shows the similarity scores for all the selected cities in the current and future periods when compared to the historical period.

4.2.1 Kano city

The results for the current period (the 2030s), under the mitigated scenario (Fig. 3), show that Kano's current average temperature conditions in the historical period reside in a different geographical region, in the Southern part of Africa around Siavonga in Zambia with a similarity score of 0.64, (See Table 1 and SF1a). For the unmitigated scenario (RCP8.5),
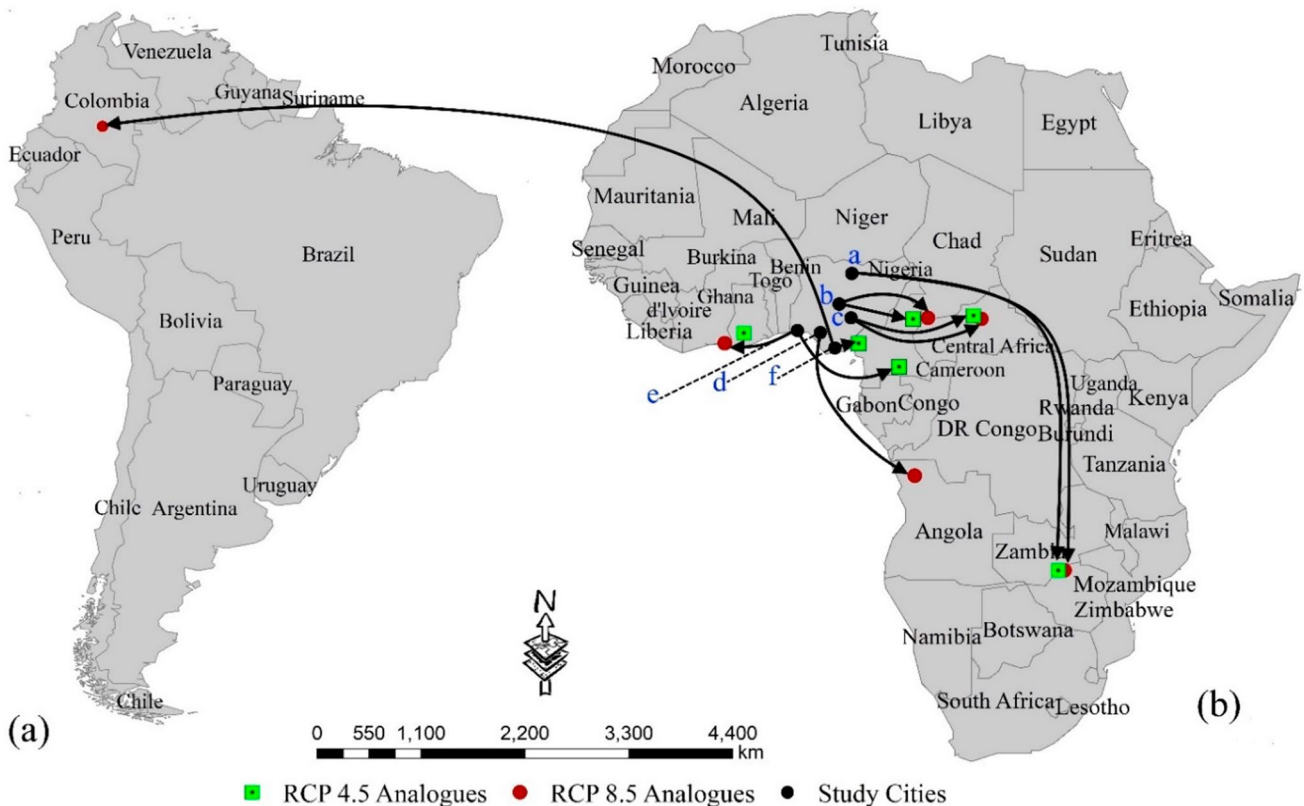
Fig. 3 Temperature analogs for the 2030s period under the RCP4.5 and 8.5 scenarios. **a** South America **b** African. **a** Kano **b** Abuja **c** Makurdi **d** Benin **e** Lagos **f** Port Harcourt
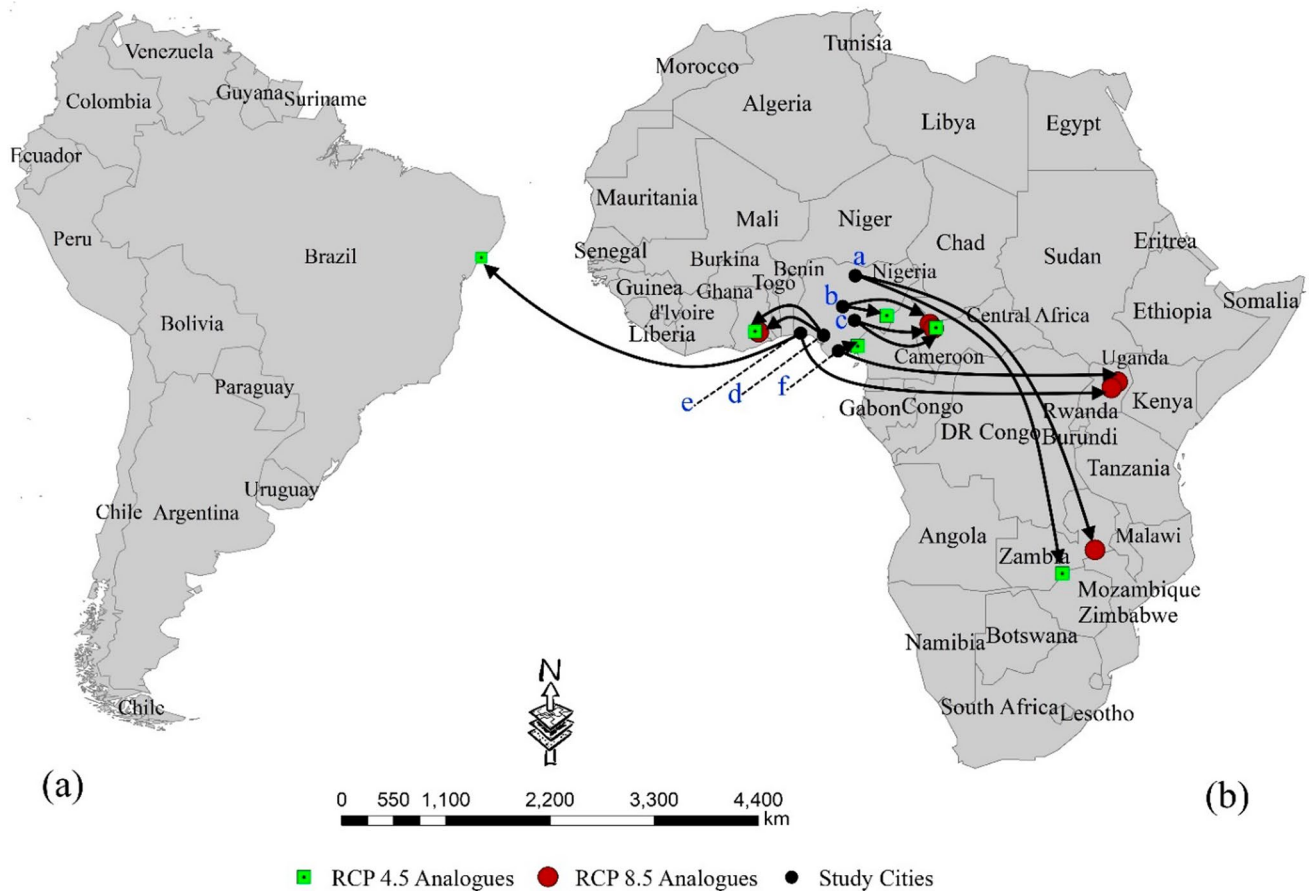
Fig. 4 Temperature analogs for the 2050s period under the RCP4.5 and 8.5 scenarios. **a** South America **b** African. **a** Kano **b** Abuja **c** Makurdi **d** Benin **e** Lagos **f** Port Harcourt

the analog is located further to the south around Mashonaland in Zimbabwe (about 3867 km from Kano) with a similarity score of 0.63 (SF1b). The lower similarity scores indicate that the temperature condition in Kano city for the current and future periods is tending towards novelty; meaning that there would be changes in the temperature condition and these changes will look more like what has not been experienced anywhere globally in the historical period. For the future period (2050s), under the scenario close to what might be expected based on current global policies and actions (RCP8.5), Kano's temperature conditions will shift to Petauke in Zambia, a place about 3828 km way from Kano city (Fig. 4). The similarity score of 0.63 (Table 1) is an indication of a low level of resemblance to the city of Kano (SF1d for temperature similarity surface). Under the RCP4.5 scenarios, the place that best represents Kano city's future temperature conditions (See Table 1 and SF1c for similarity surface) is located around Chikankanta in Zambia. Similar to the 2030s period, we found it difficult to identify very good analogs for both scenarios in the 2050s period due to the low level of similarity.

4.2.2 Abuja city

In the current period (2030s averages) under the mitigation scenario (Fig. 3), Abuja city will become most similar in average temperature to the 1971–2000 conditions of Meyo-Rey in the Northern province of Cameroon with a similarity score of 0.84. This is a place located about 789 km in the southeast direction from Abuja (SF2a for similarity surface). Meanwhile, without climate mitigation (RCP8.5 scenarios), the place with an average temperature most similar to Abuja's current condition (SF2b for similarity surface) is around Logone Oriental in the Southern region of Chad with a similarity score of 0.84 (Table 1). The results also show that in the future conditions (2050s averages) (Fig. 4), Abuja's future temperature in the mitigation scenarios will shift to the historical conditions of Adamawa (SF2c) in the north-eastern part of Nigeria (0.81 similarity score and at a distance of 471 km (see Table 1)), while the best place under the unmitigated scenario will

Table 1 Analogs and similarity scores of the cities for the current and future periods

Cities			Kano (a)	Abuja (b)	Makurdi (c)	Benin (d)	Lagos (e)	Port Harcourt (f)
Current Period 2030s	RCP4.5	Analog	Siavonga, Zambia	North Province, Cameroon	Bamingui-Bangoran, (CAR)	Ashanti Region, Ghana	East Province, Cameroon	South-west Region, Cameroon
		Similarity Scores	0.64	0.84	0.79	0.82	0.82	0.81
		Distance (km)	3830	789	1285	1133	1140	256
	RCP8.5	Analog	Mashonaland, Zinbabwe	Logone Oriental, Chad	Bamingui-Bangoran, CAR	Ugie Province, Angola	Comoe, Côte d'Ivoire	Lengupa Province, Colombia
		Similarity Scores	0.63	0.84	0.79	0.8	0.78	0.8
		Distance (km)	3867	941	1368	1821	775	8869
Future Period 2050s	RCP4.5	Analog	Chikankanta, Zambia	Adamawa, Nigeria	Paoua, CAR	Kwahu East, Ghana	Aracaju, Brazil	Mundemba, Cameron
		Similarity Scores	0.65	0.81	0.76	0.81	0.8	0.81
		Distance (km)	3814	471	857	720	4880	212
	RCP8.5	Analog	Petauke, Zambia	Ngaoundaye, CAR	Bocaranga, CAR	Kwahu South, Ghana	Soroti, Uganda	Budiope, Uganda
		Similarity Scores	0.63	0.84	0.76	0.78	0.79	0.8
		Distance (km)	3828	930	831	681	3374	2905

Central African Republic (CAR)

The two (2) periods of study are the 2030s and 2050s under the climate scenarios of RCP4.5 & RCP8.5

Similarity score = 1 indicates a perfect match, > 0.5 denotes an increasing level, < 0.5 denotes a decreasing level and 0 indicates no similarity

be more like temperature conditions found in the land-locked country of Central African Republic around Ngaoundaye (SF2d for similarity surface and similarity score of 0.84).

4.2.3 Makurdi city

The result of the 2030s period (Fig. 3) shows the location of the place with the most similar temperature condition to Makurdi's current temperature under the RCP4.5 scenarios. Generally, West and Central Africa shows more similarity for the city of Makurdi when compared to other regions (See similarity surface SF3a) however, Bamingui-Bangoran in the Central African Republic represents the best place under both scenarios of RCP4.5 (similarity score of 0.79) at a distance of 1285 km and RCP8.5 (similarity score of 0.79) at a distance of 1368 km from Makurdi respectively (Table 1) (see SF3a & b for the respective similarity surfaces). In the 2050s period (Fig. 4), the places with similar temperature conditions under both climate scenarios are located in the Central African Republic (Paoua under the RCP4.5 scenarios with similarity score of 0.76 and at a distance of 867 km) (SF3c) and Bocaranga under the RCP8.5 scenarios with similarity score of 0.76 and at a distance of 831 km (SF3d).

4.2.4 Benin city

For Benin city in the current 2030s period and under the RCP4.5 scenarios, several places with similar temperature condition can be found mostly along the coast of West Africa but the most similar location to Benin city is found in the Ashanti Region of Ghana (Fig. 3) with a similarity score of 0.82 and at a distance of 1,133 km from Benin city (Table 1). For details, see temperature similarity surface (SF4a). However, the best representation for the RCP8.5 scenarios is located in Uige, Angola with 0.80 similarity score and at a distance of 1821 km (SF4b for similarity surface). In the 2050s period and under the RCP4.5 scenarios (Fig. 4), the best representation of the future temperature condition for Benin City is cited in Ghana (Kwahu East) with 0.81 similarity score and at a distance of 720 km from Benin city. The similarity surface for the 2050s period shows that places with similar temperature for Benin city are mostly in the West to central parts of Africa under the RCP4.5 climate scenario (SF4c). Under the RCP8.5 scenarios, the most similar place is located in the Southern part of Kwahu, Ghana with a similarity score of 0.78 (Table 1) (SF4d for similarity surface).

4.2.5 Lagos city

The temperature analog for the 2030s average for Lagos city in the mitigated scenarios (RCP4.5) and the unmitigated (RCP8.5) scenario are located in the West African region (SF5a & b) [Haut-Nyong in the East Province of Cameroon for RCP4.5 (at a distance of 1140 km)] with a similarity score of 0.82, and (Roa Comoe in Côte d'Ivoire for RCP8.5 (at a distance of 775 km) with a similarity score of 0.78) (Table 1).The similarity scores shows that RCP4.5 presents a better analog when compared to the RCP8.5 for Lagos city. For the 2050s average (Fig. 3), the place that best represents the future conditions under the RCP4.5 scenarios is found far away in Aracaju (Brazil), a coastal region just like Lagos city and located about 4880 km away from Lagos while the RCP8.5 scenarios for the same period is located in Soroti, Uganda with a similarity score of 0.79. The similarity surfaces show good analogs for both RCPs (see SF5c & d and Table 1).

4.2.6 Port Harcourt city

For the city of Port Harcourt, the 2030s temperature most similar to the historical conditions under the RCP8.5 is located around Kupe-Muanenguba in the Southwest region of Cameroon (Fig. 3) with a similarity score of 0.80 (SF6b for similarity surface), while the most similar for the RCP4.5 scenarios is located in the Lengupa Province of Colombia with a similarity score of 0.81 (Table 1) (SF6a for similarity surface). The similarity scores under both climate scenarios indicates a good analog for the city of Port Harcourt. For the 2050s period (Fig. 4), the place with the most similar temperature under the RCP4.5 scenarios is located in Mundemba, Cameroon with a similarity score of 0.81 and at a distance of 212 km while Budiope in Uganda represents the most similar place to Port Harcourt city under the RCP8.5 scenarios with a similarity score of 0.8 and at a distance of 2905 km. SF6c & d shows the temperature similarity surfaces for the 2050s mitigated RCP4.5 and unmitigated RCP8.5 scenarios.

4.3 Insight from analogs

Based on the analogs approach, our findings show that the 6 selected cities will experience changes in temperature conditions for both the current 2030s and the future 2050s periods that will be similar to the temperature conditions identified in other places in the historical period considered. The most similar places to the cities in the different scenarios and periods mostly shift to places within the neighborhood of longitude (– 10° to 20°) (Figs. 3 and 4) while their spatial distribution is mainly within West, Central, and Southern Africa except for Lagos city in the 2050s (RCP4.5) (Fig. 4) and Port Harcourt city in the 2030s (RCP8.5) (Fig. 3). The best places identified as the analogs of the cities are generally south of the corresponding cities, thus indicating a north–south transect, and a warmer future [25]. This is an indication of the potential increased vulnerability of the selected cities and their population to temperature changes. This is also consistent with other studies that shows that the climate of some cities will shift mainly to their south [13, 25, 27, 70] and the potential climate risk of urban population and built-up areas may increase [20]. The overall results demonstrate that the analogues and the cities are still within the domain of the global tropical zone which occurs around the equator within the tropic of Cancer and Capricorn. The similarity score (Table 1) for Kano city is lowest when compared to all other cities, meaning that the strength of the similarity is weakest for Kano city in both the current and future periods and therefore, not a good representation of the temperature analog. Factors responsible for such poor analogs may include; atmospheric circulation patterns [72], uncertainties in climate models [73], climate change and extreme temperature events [74], topography, and unique regional characteristics [75]. These factors may influence the local climate conditions thus, making it difficult to identify direct temperature analogs for any city. Abuja, Benin, Lagos and Port Harcourt cities have higher similarity scores which is an indication of a high level of similarity with their temperature analogues.

4.4 Implications for sustainable city-related action

Towards building a sustainable city, policy designs and actions to address the social, and environmental impact through urban planning and city management [76] are the best approaches in drawing lessons from analogs. In the capital city of Abuja for example, the best representation of the future temperature conditions is located in Adamawa (RCP4.5) and Ngaoundaye (RCP8.5). The residents will experience new temperature conditions mostly similar to the Guinea savannah of Nigeria and the Sudan savannah of Central African Republic (a tropical savannah climate (type Aw) in Köppen climate classification) respectively [77] (Fig. 4). The identified analogs for the city are on the same latitude; meaning that they would tend to have similar temperature patterns [78]. This may be because they receive similar amounts of solar radiation throughout the year, thus resulting in comparable variations in seasonal temperature. Given that there is a high inflow of people into the capital city of Abuja [79], proper planning and developmental control are needed to reduce the possible future impacts of climate change as drawn from the analogues. [80] described the increasing impacts of temperature events in the analog (Cameroon) of Abuja city in the current period (2030s), 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 [81] can be adopted by Abuja city. By enacting climate friendly laws in Abuja city, reduction in the cost of adaptation could be achieved by the introduction of buildings and roads with climate induce initiatives. 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 [82] could benefit the resident of Abuja city given the administrative position of the city. Although, according to [83], adaptive capacity varies considerably in different places, cities like Abuja when compared to other cities in Nigeria are expected to be able to cope with the impacts of climate change to some extent due to the already existing level of infrastructure and urban planning [84]. Further analysis of the vulnerabilities of the analogues will go a long way in exploring the different dimensions of adaptive capacities for future developmental plans. In the immediate, the combination of environmental and infrastructural friendly initiatives such as the use of vegetation to provide benefits to mitigate extreme heat along road corridors [85], design and operation of residential buildings to reduce health risk especially in the post COVID-19 era of work from home [64] would benefit the residents of Abuja city in the face of a changing climate.

Makurdi is another traditional city known for its ancient agricultural practices, especially for small hold farmers and gardeners [86] that shares similar temperature characteristics in the current and future periods to the historical conditions of Bamingui Bangoran in Central African Republic (A region characterized by the tropical wet and dry or savanna climate) [87]. According to [88], historical data shows the need for city planners in the Central African Republic to implement urban green belts and adopt the use of green roofs to mitigate the increasing effects of surface urban heat islands.

Makurdi city can use this information to draw lessons from its analog for the current and future periods. The adoption of temperature-resistant varieties in their small-hold agricultural practices based on lessons drawn from their analogues can facilitate benefits in terms of optimizing agricultural practices. Although, in some conditions, benefits like these can only be possible if they are carried out alongside other associated factors such as sustainable land management practices and tree based initiatives [89] for agricultural productions [90].

The southern region of Ghana (A region that falls within the wet semi-equatorial climatic zone), represents the temperature analogues of Benin city's current and future temperature conditions in RCP4.5 and RCP8.5 climate scenarios. With the continuous occurrence of extreme weather events such as severe heat in Ghana [83], an in-depth understanding of its impacts on residents as a place most similar to the temperature conditions of Benin city can provide a useful guide in climate policy formulations. Given that Benin city is a fast developing major city in Nigeria [43], the integration of technological solutions in the housing sector such as improved open ridge ventilated thatched roofs may reduce the existing vulnerabilities of the city to heat stress [75]. Since construction activities in areas surrounding cities often leads to expansion, the use of building materials for future constructions such as light-colored paints that would increase the reflectivity of sunlight can also help to reduce the heat load of buildings within the city [11]. It is imperative for the city planners to evaluate different cooling strategies in buildings [91] especially with the knowledge of their analogues in the context of climate change and take preventative actions to enhance the city's resilience. Benin city can benefit from such initiatives in order to combat and prepare for the potential impacts of temperature especially when availed information from their analogues.

For the ancient and traditional city of Lagos with a projected population of over 32 million by the mid-twenty-first century [92], the best representation of its temperature is located to the south of the city for both climate scenarios of 2030s period (Fig. 3) and to Aracaju in Brazil, a wet equatorial climate [93] in the RCP4.5 scenarios of 2050s (Fig. 4). This shows that the residents of Lagos city will experience temperature conditions of the wet equatorial climate of Brazil which is different from the coastal mangrove savannah of Nigeria in the 2050s period of Mitigation scenario. A change like this would be equivalent to a shift in the temperature conditions of the city to a place approximately 4,880 km away. 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 temperature on the residents of Lagos city in the future given that urban heat island has become intense in Aracaju [93]. [94] showed that semi-open spaces and relatively suitable vegetation brings more favorable environmental conditions to urban areas while outdoor acoustic comfort has been found to be an essential aspect of urban design that affects the behavior of city dwellers, and the general environmental comfort of the residents [95]. Thus, the government of Lagos city and the administrators can incorporate more parks and open spaces into the designs of new districts in order to harness the lessons drawn from their analogues and at the same time adapt to the expected future temperature changes. Although Lagos is fast developing with more modern infrastructures when compared to other cities in Nigeria [96], 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 [97], increase shading [98] and improve exposure to wind. This will improve the urban environments, reduce energy consumption, greenhouse gas emissions, cut overall cost, and improve the residents' temperature experience [99]. 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 such areas thus, reducing the vulnerability of the residents. Furthermore, increasing the green areas along the roads and residential areas to facilitate the cool island effect will help mitigate the impact of heat [85] and subsequently reduce the energy demands for cooling. Studies have shown that the combination of the low-albedo pavements and covering half of the street with trees can produce the most effective conditions for thermal comfort [100]. An understanding of the changes in the conditions between the city and the analog could provide a unique opportunity to establish the necessary effective response strategies and climate-relevant action can be shared or transferred.

Port Harcourt city can consider how its analog, the Southwestern region of Cameroon (A region with an equatorial climate of the western highlands of Cameroon) [101] has taken actions to combat their temperature-related challenges. Given that temperature-based indices in Cameroon cities are on the increase [62], deeper insights into the implications will be of great usefulness to policymakers and stakeholders in the design of sustainable responses to temperature-related hazards for the city. Initiatives such as the use of suitable heat-resistant materials for the construction of houses as used in Cameroon in the historical period [102] can serve as lessons for facilitating the development of more specific adaptation strategies in the housing sector. In planning for the future, the adoption of renewable energy technologies such as solar walls for the generation of power [103] and in the short term, housing designs for more ventilation of rooms to reduce urban heat [104] are adaptation measures that could be incorporated into the planning processes for the city.

Furthermore, assessing the micro-environment of open air by the city planners could be key to enhancing the outdoor thermal conditions [38] for the residents of Port Harcourt. Therefore, a reliance on shared knowledge and inter-connected climate adaptation efforts could be key in breaking the barriers for future planning and sustainable development.

Ultimately from our studies, and other applications of analogues, what temperature analog offers is not a new model of the future but rather a means to communicate existing scenarios such that their predictions are less abstract but more placed based and context related. A crucial step in support of analog predictions is to encourage educators, and social scientist to assess the extent to which analog can help increase climate change engagement and awareness. 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. The findings from our studies has provided a spatial and visual representation of the current and future temperature conditions of these traditional and economic cities for governance by simplifying the complexities and forecasting the changes in a simple manner in order to provide insights into adaptation.

5 Conclusion

Base on the temperature analog analysis, major traditional and economic cities in Nigeria will experience changes and shifts in their temperature conditions in the current and future periods under different climate scenarios. The outcome of the study reveals that the cities will experience changes similar to the conditions of other identified places in the historical period based on their level of similarities. The similarity score for Kano city is lowest when compared to all other cities, meaning that the strength of the similarity is weakest for Kano city in both the current and future periods and may therefore not be a good representation of the analog. The places identified to be most similar to the cities in the different scenarios and periods are mostly spatial distributed within West, Central, and Southern Africa. The direction of the cities shift to their analogues is generally to the south of the corresponding city, which is an indication of potential warming. Such temperature change is expected to have direct implications on the residents of the cities, who will have to adapt to new temperature-related issues. By providing information on the future or current conditions of the cities in the historical period, land managers and city planners will understand and contextualize the future, in order to facilitate efforts in the establishment of specific strategies. This study suggests using analogs methodology for urban climate management and provides valuable insights for built environment professionals and environmental agencies to develop targeted strategies for addressing possible temperature challenges in cities. We highlighted a need for more studies that target city-to-city interactions to draw lessons and form a foundation for informed decision-making to promote environmental sustainability and urban well-being. Although literature emphasizes the implications of blanket adaptation strategies without careful considerations, by adopting comprehensive integrated approaches (via transfer and scale-up of local solutions), multidimensional resilience can be developed to address the challenges, while simultaneously improving livability, and sustainability. Therefore, this study illuminates the possible applications of analog as an approach to solving several environmental issues in rapidly changing, heavily built-up and densely populated cities in Nigeria and West Africa by extension in accordance to achieving sustainable city goals (SDG 11).

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Declarations

Competing interests The authors declare no competing interests.

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