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# Air temperature, relative humidity, climate regionalization and thermal comfort of Nigeria

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**ABSTRACT:** Planners and policy makers require information about the regions for which they are responsible. However, it seems that many developing countries, including Nigeria, are not adequately prepared either for their current climates or for the impact of climate change because they lack sufficient information. We have therefore examined the variations in the thermal condition in terms of the temperature, relative humidity, effective temperature (ET), temperature–humidity index (THI) and relative strain index (RSI). We studied the spatial and temporal (1951–2009, 1951–1980, 1981–2009, decadal, seasonal and monthly averages) variations in the thermal climate of Nigeria, and we divided Nigeria into thermal climate regions for effective climate change management. Mean annual minimum, mean and maximum temperatures (with their standard deviations) were 21.4 (3.5), 27.1 (2.7) and 32.8 (3.4) °C, respectively, while the overall mean relative humidity was 62 (24.8)%. Mean ET, THI and RSI were 24.3 (0.85), 24.8 (1.83) and 0.2 (0.18) °C, respectively. The ET, THI and RSI provided contrasting expressions of thermal comfort for Nigeria, because of its varied climate. We also found that elevation; the movement of the Inter Tropical Discontinuity and urbanization affect thermal comfort in Nigeria. We conclude that thermal stress has increased in Nigeria from 2000 at most stations, especially in the south and north-western regions, and that Nigerian thermal comfort climate is heterogeneous and requires analysis of multiple thermal indices.

**KEY WORDS** climate regionalization; spatial and seasonal variation; physiologic climate; thermal stress; tropical climate

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## 1. Introduction

The relation between man and climate is reciprocal in the sense that man responds to variation in climate by insulating buildings, heating and air-conditioning. Man's aim is to be comfortable despite the climate, and this gives rise to the notion of thermal comfort. Thermal comfort has been studied since the start of 20th century, and improvements in building techniques, as well as discoveries in central heating and air conditioning systems have led to improved comfort in indoors, even in the hottest and coldest climates (Brager and de Dear, 1998). Several indices of comfort and mathematical models to predict thermal comfort and discomfort have also been developed (Gómez *et al.*, 2004; Watkinson *et al.*, 2004; Kiang *et al.*, 2006). For most indoor conditions, the efficiency of a person or group of people has been described 'as being bound up in the climatic conditions in which they work and live' (Han *et al.*, 2007). Han *et al.* (2007) argued that buildings are designed to suit the climate within which they are located and the functions for which

they are intended. This, however, is probably untrue for most developing countries, especially in areas with planning problems (Adepoju, 1982; Adebayo, 1987; Jauregui, 1991).

Several investigators have also shown that variation in the heat indices, especially temperature, have significant relations with human mortality (Kalkstein and Smoyer, 1993; Alcamo *et al.*, 2007; Lin *et al.*, 2011) and prevalence of certain diseases (Greenwood, 1999; Coêlho *et al.*, 2010). The young children (Bunyavanich *et al.*, 2003), elderly and pregnant women are often considered to be particularly vulnerable to temperature extremes that can cause cardio-respiratory and skin diseases (Balbus and Malina, 2009). With global increase in temperature, especially from the 1960s and the tendency for further warming (Le Treut *et al.*, 2007), as well as the concern for the increased urbanization in developing countries, concerns for thermal comfort have become important in the programme of the World Meteorological Organisation (WMO) (Jauregui, 1997). Studies on temperature and humidity (Arundel *et al.*, 1986; Wolkoff and Kjaergaard, 2007) have showed the relevance of climate and weather to human health (Kalkstein and Valimont, 1986), migration, retirement, tourism (Mieczkowski, 1985; Jendritzky *et al.*, 2001) and energy requirements,

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among others (Jauregui, 1993). Extreme climates can increase mortality (Hajat *et al.*, 2005; Greenwood, 2006) and forced migration (Meze-Hausken, 2000). Knowledge of the thermal climate of any region is therefore vital for planning on health, urban development, tourism and migration, among other matters (De Freitas, 2003; World Health Organisation, 2011).

Despite the importance of thermal conditions both regionally and nationally, little is documented on their effect on human comfort in many developing countries, including Nigeria (Boko *et al.*, 2007; World Health Organisation, 2011). These countries, however, comprise a significant proportion of the world's most rapidly urbanizing regions. The United Nations (United Nations, 2008) suggested that more than 90% of future population growth will be concentrated in cities in developing countries, and a large percentage of this population will be poor. Few studies, nonetheless, have been undertaken in Nigeria, most of which have been limited to either indoor microclimate (Ajibola, 2001; Ogbonna and Harris, 2008) or urban microclimates (Olaniran, 1982; Adebayo, 1991; Akinbode *et al.*, 2008).

On the other hand, recent studies have shown that heat-induced mortality resulting from meningitis has increased in the north and middle belt of Nigeria (Greenwood, 1999; Mohammed *et al.*, 2000; Greenwood, 2006). Sawa and Buhari (2011) also predicted that meningitis and measles would increase by 6 and 19 persons per thousand, respectively, for every 1 °C increase in temperature in their study on Zaria, in northern Nigeria. In Greece, Matzarakis (2001) suggested that temperature-related diseases will most likely increase as urbanization increases, while in California, USA, Ostro *et al.* (2011) associated temperature increases with increased mortality and hospital admissions and in Brazil, significant link exists between the effective temperature (ET) and hospital admissions for respiratory diseases (Coelho *et al.*, 2010).

Although records of mortality and hospital treatments are fraught with uncertainties in many developing countries (Kwast *et al.*, 1986; Williams and Boren, 2008), we know that urbanization in Nigeria, as in most developing countries, is rapid, and the explosion of urban population has not been matched by a change in social, economic and technological development (United Nations population Fund, 2007; WHO, 2011). Public infrastructure, social and health services have been neglected, and urban planning and zoning have been slow or stagnant in many cases. Consequently, there is the preponderance of large proportion of urban dwellers living and working under conditions that make them vulnerable to effects of climate. These are often poor people, and a sizeable proportion of the Nigerian population is in this category (Adepoju, 1982). Certain urban characteristics, including structure and geometry can affect the pattern of movement and distribution of the air and solar radiation, with important implications for thermal comfort (Jonsson, 2004; Candido *et al.*, 2010; Krueger *et al.*, 2011).

We have examined the spatial and temporal (1951–2009, 1951–1980, 1981–2009, decadal, seasonal

and monthly averages) variations in the thermal climate of Nigeria, in terms of temperature, relative humidity, ET, temperature-humidity (THI) and relative strain (RSI) indices. We have divided Nigeria into thermal climate regions for effective climate change management. We have adopted a conceptual framework that links thermal comfort and human heat balance with certain meteorological elements, body conditions and some intervening conditions (Figure 1). Results presented here are those of the meteorological factors. The main hypotheses are that (i) thermal stress increased in Nigeria between 1951 and 2009, and that (ii) thermal comfort in Nigeria exhibits direct relationship with proximity to the influence of the moisture-laden maritime air mass from the Atlantic Ocean in the south or the dry continental air mass from the Sahara.

## 2. Methods

### 2.1. Site description

The study area, Nigeria, lies between 4–14°N and 3–15°E in the southeastern edge of the West African region. Nigeria's land area is about 923 800 km<sup>2</sup>, and is about 14% of West Africa. The Atlantic Ocean, Sahara desert and Cameroon Mountains, which form the southern, northern and eastern boundaries, exert influences on the country's climate systems (Ileje, 2001). Nigeria is characterized by two main seasons; dry and rainy seasons. The dry season is accompanied by a dust-laden wind from the Sahara desert, known as Harmattan, which is brought by the Tropical Continental (cT) airmass, while the rainy season is heavily influenced by the Tropical Maritime (mT) from the Atlantic Ocean (Figure 2). The local climate in the north central region may also be more influenced by the high elevation in the region than the south (Figure 3).

Nigeria is generally classified into three climate types (Ileje, 2001); tropical rainforest climate, tropical savanna climate, highland climate or montane climate. The tropical rainforest climate, designated by the Köppen climate classification as 'Af', characterises the southern region. The Tropical rainforest is sub-grouped into the tropical wet and tropical wet and dry climates as mapped by Dada *et al.*, (2008). It is characterized by small temperature range, throughout the year, and usually convective storms, as a result of its proximity to the equatorial climate. The Tropical savanna climate comprises the Guinea, Sudan and Sahel savanna, and characterizes most of the central and northern regions. The Guinea belt occupies the limits of tropical rainforest climate, and extends to the central part while the northern fringe is occupied by the tropical (Sudan) savanna climate. The north-eastern fringes exhibit the Sahelian climate (Figure 4). The tropical savanna climate exhibits a well-marked single peak rainy season and a dry season. Mean temperature in this region exceeds 18 °C throughout the year, and the dry season, which usually occurs from December to March, is hot and dry with the Harmattan wind, prevailing

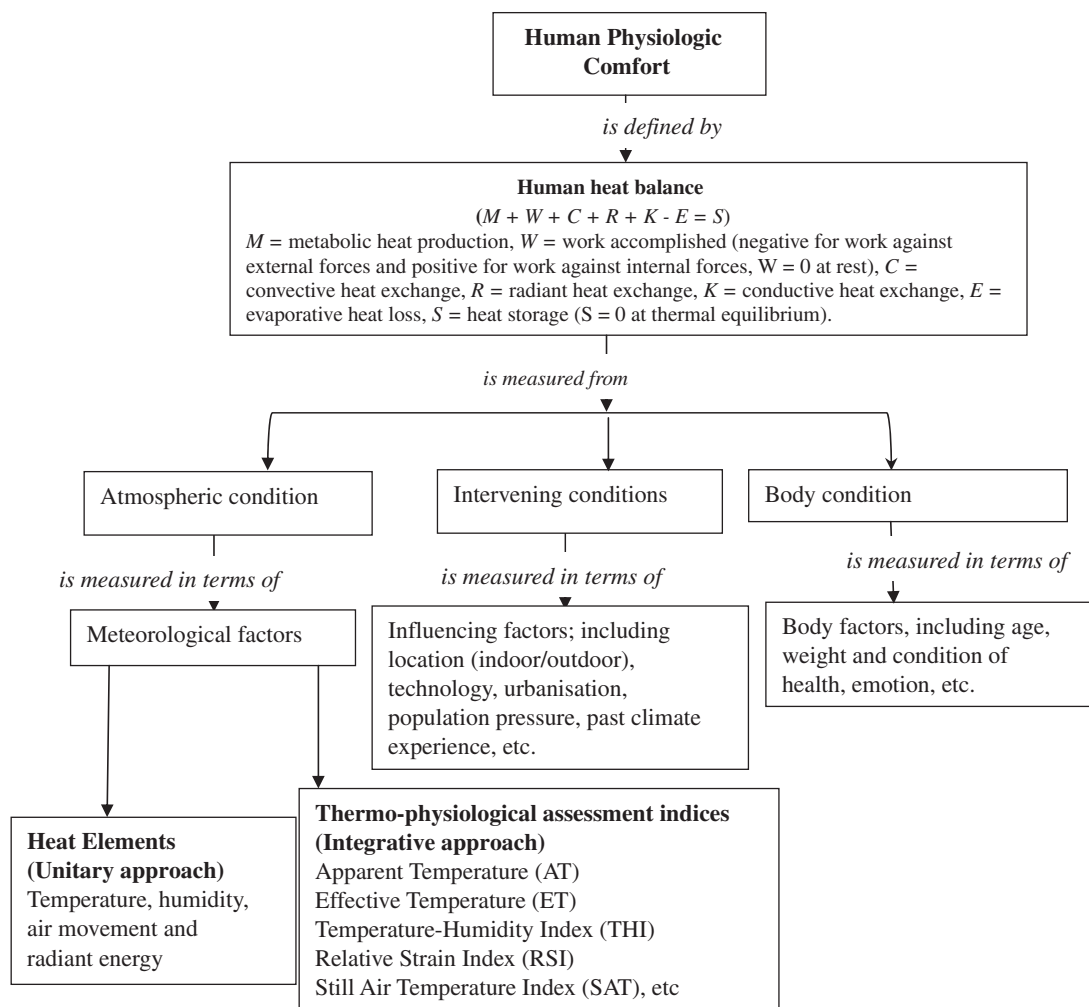


Figure 1. Human biometeorological assessment of the thermal components of different climate. This study has only focused on meteorological factors.

throughout this period. 'Highland climate' (Ileje, 2001) or montane climate is experienced on highlands regions in Nigeria. Highlands with montane climate in Nigeria exceed 1520 m above sea level. Because of their location in the tropics, this elevation provides the settlements on the mountains and the plateau regions standing above this height, a cool montane climate.

With a population of more than 140 million spread over an area of 923 800 square kilometres (National Population Commission, 2006), Nigeria is the most populated country and one of the largest countries in Africa. Estimated annual population growth is 2.5%. The urban population as at 2010 was about 49% of the total population, and is projected to increase by 3.8%, annually (United Nations Statistics Division, 2013, Table 1). Table 1 also shows that deforestation and fossil fuel generation have significantly increased; forested area is only 10.8%. Almost all the 37 administrative headquarters (including the Federal Capital, Abuja) are densely populated (about 1000 people per square kilometre). Akinbode *et al.* (2008) studied a typical administrative city in Nigeria, and found that it could create a significant island of heat (0.5–2.5 °C) during the daytime. Until recently, when

some political administrators encouraged city greening programmes, involving growing plants in the hitherto entirely built up areas (Ojo and Kayode, 2006), the major systems of land use encouraged widespread removal of vegetation for urban development, a condition known to affect the local climate.

## 2.2. Data

Data used for this study were the monthly temperature and relative humidity records for 59 years (1951–2009). Seasons considered are dry (November–March), wet/rainy season (April–October), and the Harmattan period (December–February). Data on wind, radiant energy and other heat elements (Lee, 1953) that would have also been analysed were either incomplete or unavailable during the time of this research. On the basis of the availability of data for all the existing 55 meteorological stations in Nigeria (Aderinto, 2006) and the difficulty of seeking a representative distribution of stations, all the stations were screened for data availability and completeness, before final selection of stations were made. A nest of 2° × 2° grid cells was overlaid on a map of Nigeria. Although, we considered every station

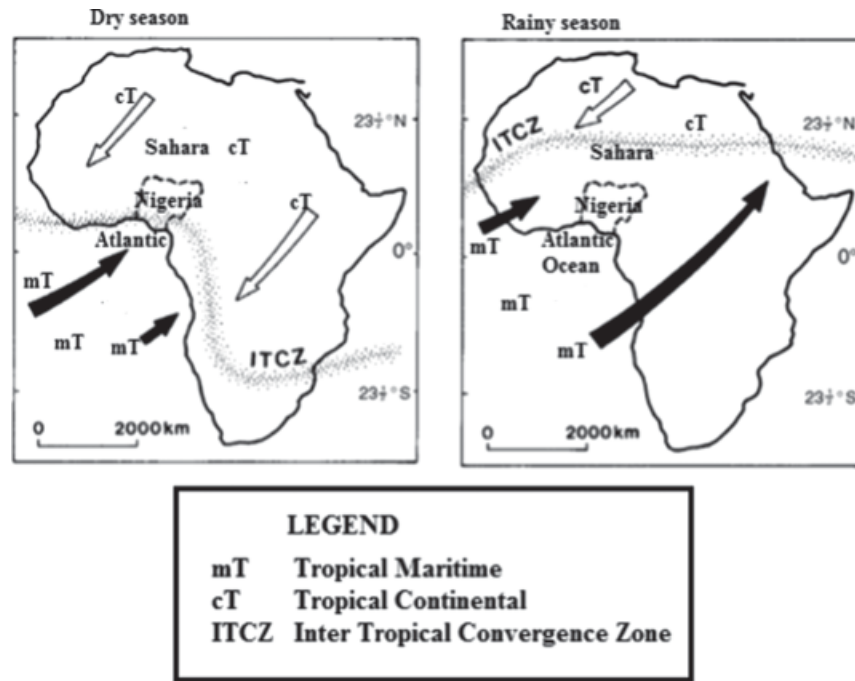


Figure 2. Nigeria in Africa, and the seasonal direction of the air masses and the Inter Tropical Convergence Zone that determine the season in the region.

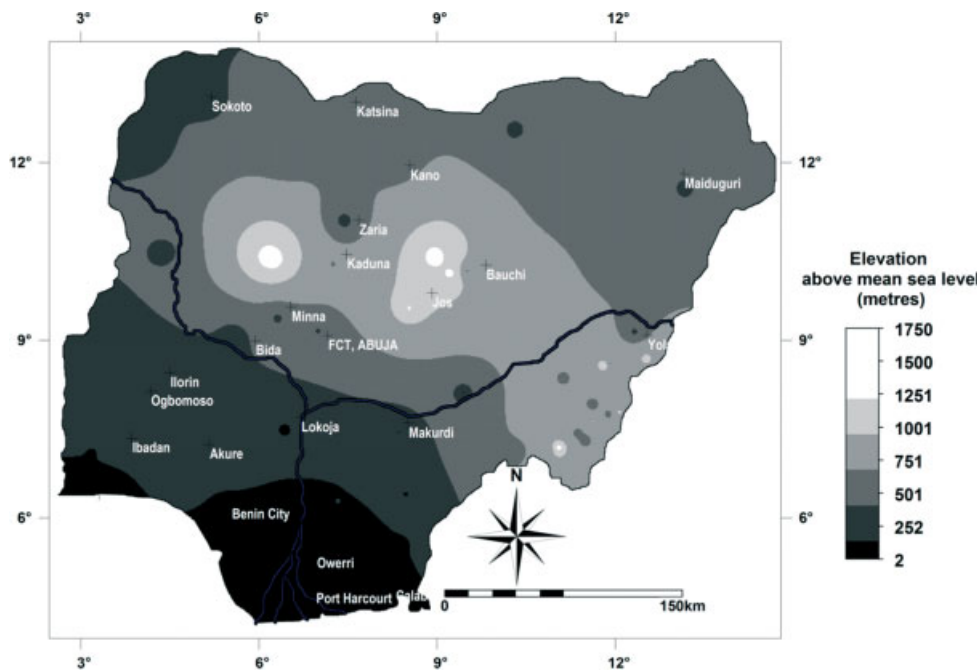


Figure 3. Basic elevation map of Nigeria.

in each grid cell as a potential representative, only meteorological stations with temperature and relative humidity data from 1951 were used. Data were, however, unavailable for most stations between 1967 and 1970, as a result of the Nigerian civil war at that time (Nafziger, 1972 for information on Nigerian civil war). Data were also examined for spurious values and evidence of non-climatic heterogeneity and instrumental errors as advised by the World Meteorological Organisation

(1989). Consequently, meteorological stations, for which data were missing for more than 5 years in a row (other than 1967–1970) and those with significant number (upward of about 10%) suspect data were removed.

In all, 18 stations (i.e. Yelwa, Sokoto, Bauchi, Nguru, Potiskum, Maiduguri, Katsina, Yola, Makurdi, Ilorin, Lokoja, Bida, Jos, Warri, Ikeja, PortHarcourt, Benin and Calabar) were selected. Selected stations were regrouped based on climate types i.e. the Tropical Rainforest;



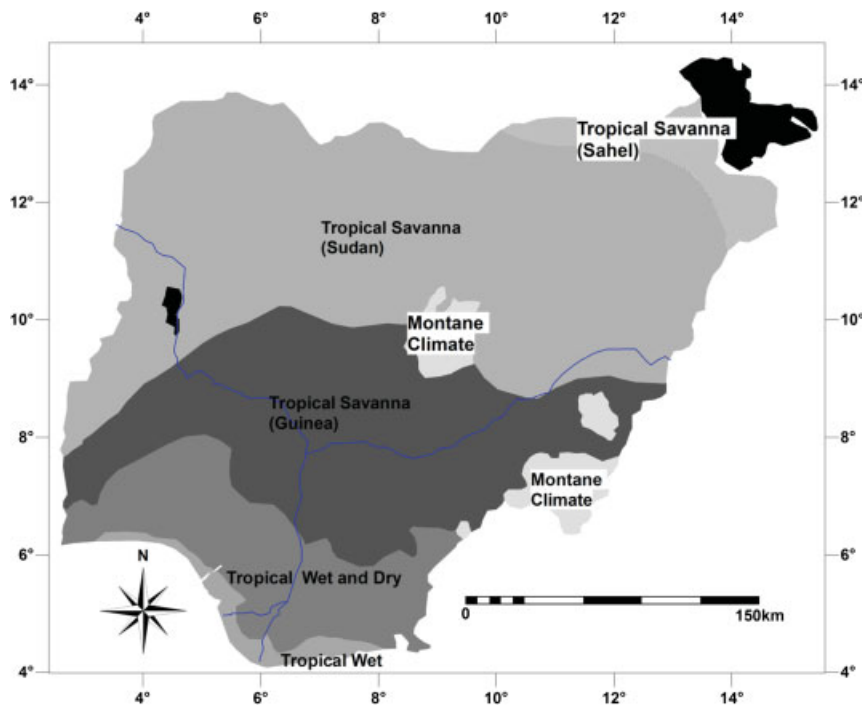


Figure 4. Basic map of Nigerian climates.

Table 1. Some parameters of urban and population growth in Nigeria.

Variables	Specifics	Rate
Landuse	Deforestation	4000 km <sup>2</sup> /year
	Reforestation	10 km <sup>2</sup> /year
	Forested area (2008)	10.8%
Urban Population	Annual growth	3.8%
	Urban Population in 2004, 2010	45%, 48.9%
Rural Population	Annual growth	1.8%
Total population	Population density in 2004, 2009	137.6, 167.5 persons/km <sup>2</sup>
	Annual growth	2.5%
	Total fossil fuels emission	1951
1980		18 586 000 tonne
2008		26 113 000 tonne

United Nations Statistics Division (2013), Carbon Dioxide Information Analysis Centre (2012).

consisting of the tropical wet (represented in this study by Warri and Port Harcourt) and tropical wet and dry climates (represented in this study by Ikeja, Benin and Calabar), the Tropical Savanna; consisting of guinea (represented by Bida, Ilorin, Lokoja and Makurdi), sudan (represented in the study by Sokoto, Bauchi, Katsina, Yelwa, Potiskum Maiduguri and Yola), and Sahel (represented in the study by Nguru savanna, and montane region (represented by Jos) (Figure 5).

### 2.3. Determination of selected integrative indices

Previous studies on Nigeria and elsewhere (Eludoyin and Adelekan, 2013; Eludoyin, 2013 for records of previous studies and indices considered) suggest that

ET, temperature-humidity index (THI) and relative strain index (RSI) are important as indices of thermal comfort in the tropics, and so these have been selected for this study. The values of the indices (ET, THI and RSI) were estimated from the respective records of temperature and relative humidity for each station, and for different period (diurnal and monthly). The formulae used for computation of ET, THI, and RSI have been found to be valid and generally accepted for use in Nigeria and the tropics (ET: Ayoade, 1978; Olaniran, 1982; Ogbonna and Harris, 2008, THI: Olaniran, 1982; Unger, 1999 and RSI: Unger, 1999, Alessandro and de Garin, 2003). The ET, THI and RSI were calculated with the empirical Equations 1, 2 and 3:

$$ET = T - 0.4(T - 10) \left(1 - \frac{H}{500}\right) \quad (1)$$

$$THI = 0.8T + \frac{HT}{100} \quad (2)$$

$$RSI = \frac{[10.7 + 0.74(T - 35)]}{44 - 0.0075HV} \quad (3)$$

where  $T$  is the mean temperature of the air (°C),  $H$  is relative humidity (%),  $V$  is the saturation vapour pressure (hPa), and is estimated as  $V = 6.11 \times 10^{\frac{7.5T}{237.7+T}}$ .

### 2.4. Analysis and descriptive mapping

Spatial and seasonal variations were estimated with the analysis of variance (ANOVA), and linear regression analysis was used to determine the trends, and with due caution to forecast future values. We used the Integrated Land and Water Information System

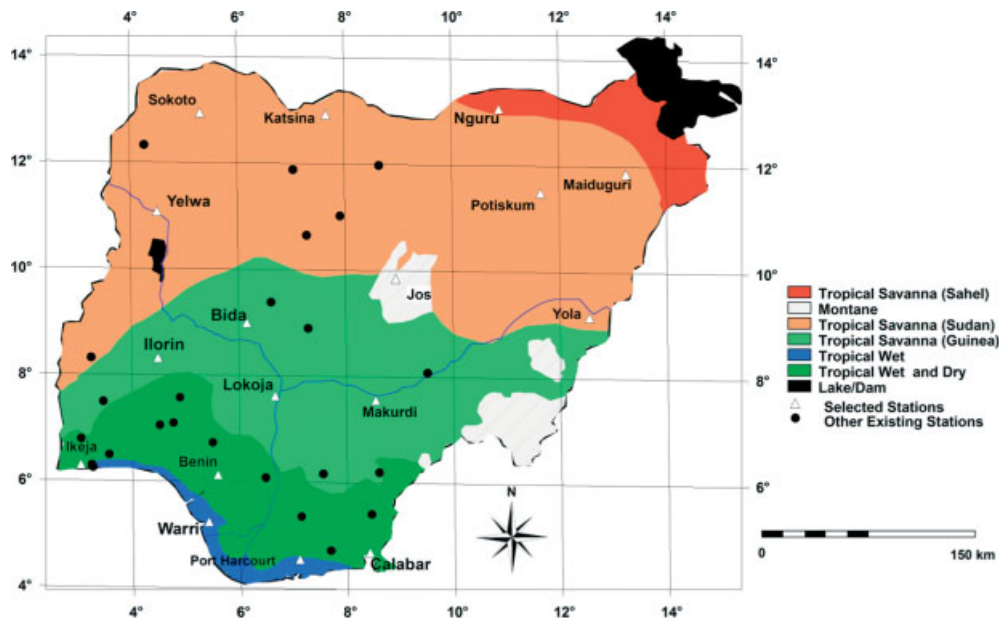


Figure 5. Distribution of meteorological stations in Nigeria. Stations that are selected for this study are labelled.

(ILWIS version 3.3) (ITC, Eschende, Netherlands) for mapping as documented by Eludoyin and Adelekan (2013).

### 2.5. Delineation of thermal climate zones in Nigeria

We delineated the thermal climates in Nigeria for the years 1951–2009 with values of indices of thermal climates (ET, THI and RSI) above or below thresholds for comfortable climate ( $18.9\text{--}25.6\text{ }^{\circ}\text{C}$ ,  $15\text{--}24\text{ }^{\circ}\text{C}$  and  $0.1\text{--}0.2$  (ratio, no unit) for ET, THI and RSI, respectively), subsequently converting the frequencies to their percentages, because the stations had differing amounts of data. Heat stress occurs when ET index is greater than  $25.6\text{ }^{\circ}\text{C}$  or when THI is greater than  $24\text{ }^{\circ}\text{C}$  or RSI greater than 0.2. Cold stress occurs with  $\text{ET} \leq 18.9\text{ }^{\circ}\text{C}$ ;  $\text{THI} \leq 15\text{ }^{\circ}\text{C}$  or  $\text{RSI} \leq 0.1$  (Nieuwott, 1977, Ayoade, 1978, Kyle, 1994, Eludoyin and Adelekan, 2013). We subsequently classified the stations into five zones using the *k*-means cluster technique with ET, THI and RSI data. ‘Region 1’, with the fewest periods when the thermal indices exceeded the thresholds, was classified as the ‘most’ thermally comfortable climate, while ‘Region 5’, with most periods when thresholds of thermal comfort were exceeded, was classified as most ‘thermally stressed climate’. Regions 2, 3 and 4 are transitory zones within 1 and 5, with Regions 2 and 3 being more thermally comfortable than ‘Region 4’.

## 3. Results

### 3.1. Mean (1951–2009) thermal variations in Nigeria

Table 2 lists the results of descriptive analysis of the variables. The overall average minimum temperature for

all the stations was  $21.4\text{ }^{\circ}\text{C}$ . Minimum temperatures were below the overall average in the tropical savanna and montane climate regions. Mean minimum temperature ranged between  $16$  and  $23.1\text{ }^{\circ}\text{C}$ , while the mean annual maximum temperature was between  $27.6$  and  $35.3\text{ }^{\circ}\text{C}$ . The mean maximum temperature in all stations within the savanna was higher than its overall average ( $32.8\text{ }^{\circ}\text{C}$ ), except at Bauchi and Ilorin. The montane, Tropical Wet and Dry and Tropical Wet climate regions, however, had lower (than the overall average) mean maximum temperature. In addition, annual mean temperature ranged between  $21.8$  and  $28.6\text{ }^{\circ}\text{C}$ , while the mean relative humidity varied between  $36.5$  and  $85.1\%$ . The Sahel and Sudan savanna and montane regions were characterized by lower relative humidity than the overall mean ( $62\%$ ). Variations in both temperature and relative humidity increased from south towards the north, except for few stations in the guinea and sudan savanna which exhibited higher variability than the sahel.

Table 2 also reveals that the lowest and highest mean annual ET occurred at Jos ( $19.4\text{ }^{\circ}\text{C}$ ) and Warri ( $26.1\text{ }^{\circ}\text{C}$ ), in the montane and tropical wet climate regions, respectively. Annual ET values at most of the stations within the Sudano–Sahelian (Bauchi, Katsina, Maiduguri, Nguru and Potiskum) and montane (Jos) climate regions are lower than the overall average ( $24.3\text{ }^{\circ}\text{C}$ ). Stations within the guinea savanna, and tropical rainforest on the other hand, exhibited higher ET than the overall average. Similarly, highest mean THI ( $26.3\text{ }^{\circ}\text{C}$ ) occurred in Lokoja (Guinea savanna) while the montane station exhibited the lowest ( $19.6\text{ }^{\circ}\text{C}$ ) mean THI. Highest RSI ratio (0.2) occurred at Warri in the Tropical wet climate while the montane region exhibited the smallest ratio (0.01). However, further investigation will be required to

Table 2. Descriptive statistics of temperature, relative humidity and thermal climate at selected meteorological stations in Nigeria (1951–2009)

Climate region	Station	Temperature (°C)						Relative Humidity (%)		ET (°C)		THI (°C)		RSI (ratio)	
		Minimum		Maximum		Mean		M	SD	M	SD	M	SD	M	SD
		M	SD	M	SD	M	SD								
Tropical savanna (Sahel)	Nguru	21.2	4.4	35.3	3.6	28.2	3.5	36.5	21.1	23.1	1.5	24.2	1.5	0.17	0.05
Tropical savanna (Sudan)	Katsina	19.4	4.3	33.7	3.4	26.5	3.5	38.9	23.5	22.5	0.6	23.3	0.6	0.13	0.02
	Sokoto	22.0	3.6	35.2	3.2	28.6	3.0	42.7	23.6	24.4	0.6	25.4	0.6	0.19	0.03
	Maiduguri	20.1	4.6	35.3	3.6	27.7	3.6	39.9	20.7	23.5	0.6	24.4	0.6	0.16	0.02
	Potiskum	19.7	4.5	34.4	3.3	27.0	3.4	39.5	23.9	22.4	1.3	23.3	1.2	0.13	0.10
	Yelwa	21.3	3.6	34.1	3.0	27.7	2.3	60.7	19.1	24.9	0.5	25.5	0.7	0.18	0.06
	Bauchi	19.0	3.5	32.7	2.8	25.8	2.6	46.7	23.1	22.4	0.7	23.1	0.7	0.09	0.10
Montane	Yola	21.7	3.2	34.7	3.1	28.2	2.4	55.2	23.5	24.9	0.9	25.7	0.9	0.21	0.05
	Jos	16.0	2.3	27.6	2.3	21.8	1.7	50.0	25.9	19.4	0.3	19.6	0.4	0.01	0.01
Tropical savanna (Guinea)	Bida	22.8	1.8	33.7	2.8	28.3	1.9	64.4	18.1	25.5	0.8	26.1	0.6	0.21	0.06
	Ilorin	21.3	1.7	32.2	2.6	26.8	1.6	74.4	11.6	24.4	0.5	24.9	0.5	0.17	0.02
	Lokoja	22.8	2.0	33.0	2.4	27.9	1.7	73.4	8.2	25.9	0.7	26.3	0.6	0.22	0.04
	Makurdi	22.3	2.5	33.3	2.6	27.8	1.8	69.8	14.2	25.4	0.9	25.9	0.7	0.21	0.04
Tropical Wet and Dry	Ikeja	23.1	1.3	30.9	1.9	27.0	1.4	82.6	5.8	25.3	0.6	26.1	0.6	0.21	0.04
	Benin	23.0	0.8	31.3	2.0	27.1	1.4	83.9	5.7	25.9	0.6	26.1	0.6	0.21	0.04
	Calabar	22.8	1.0	30.6	1.8	26.8	1.2	85.1	5.0	25.7	0.9	25.9	0.8	0.19	0.09
Tropical Wet	Warri	23.1	0.9	31.4	1.8	27.3	1.2	83.9	4.8	26.1	0.4	26.3	0.9	0.22	0.02
	Port Harcourt	22.4	1.2	31.1	1.8	26.7	1.1	83.4	5.5	25.6	0.4	24.8	1.2	0.20	0.03
Overall mean		21.3	1.9	32.8	2.0	27.1	1.5	61.7	18.3	24.3	1.7	24.8	0.8	0.17	0.05

M represents the mean of the monthly average from 1951 to 2009. SD is the standard deviation of the monthly averages from 1951 to 2009 ( $n = 708$ ).

understand the effect of this on the interpretation of RSI. Except for the large variation (large standard deviation) in ET and THI at Nguru (Sahel), Potiskum (Sudan) and Port Harcourt (tropical wet), values of variation in other regions were less than 1 °C.

In addition, Figure 6 shows the spatial distribution of the 59 (1951–2009) years mean distributions of temperature, relative humidity, ET, THI and RSI for Nigeria. The southern region (including the Tropical Wet, Tropical Wet and Dry climate and some parts of tropical savanna) were characterized by higher mean minimum temperature than the north-central part of the Sudan savanna and montane regions. The station (Jos) in the montane region had the lowest mean minimum temperature. Lower mean maximum temperatures also occurred at Calabar and Jos than elsewhere in Nigeria. The northern region had the highest maximum temperature, with peaks around Sokoto, Nguru and Maiduguri. The mean ET pattern (Figure 6(e)) shows the south and the northwest at the margin of heat stress (24–26 °C), and the northeast as thermally comfortable (22–24 °C). Heat stress declines towards the montane, where the lowest (18–22 °C) was recorded. Earlier results (Table 2) showed that variation in ET is greater in the Sahel (Nguru) and a station in the Sudan savanna (Potiskum). In terms of THI, this region was shown to be thermally comfortable, while the montane location was also classified as most comfortable (Figure 6(f)). Significant thermal heat stress (THI greater than 26 °C) occurred mainly around Lokoja, Ikeja, Benin and Warri in the Guinea and tropical forest

(Tropical wet and dry, and tropical wet climates) region. Like the results on THI, the RSI map (Figure 6(g)) also shows area around Bida, Lokoja, Ikeja, Benin and Warri as most thermally stressed, and the region around the montane climate as most thermally comfortable.

### 3.2. Variation in temperature, relative humidity and thermal comfort index between 1951–1980 and 1981–2009

If we compare the average values for 1951–1980 with those for 1981–2009 we see that all the temperatures have increased at most stations by less than 1 °C (Figure 7). Minimum temperature increased by 1–2 °C in the northwest, Sahel (Nguru), Ikeja and around Bauchi. Nguru, Potiskum, Bauchi and Niger-Delta areas exhibited 0.5–1 °C increase in the maximum temperature but other areas, except Ilorin and Yelwa in the west showed a smaller (less than 0.5 °C) increase. The mean temperature showed between 1 and 2 °C increase at Nguru while increase at other regions were less than 1 °C. The mean temperatures of some areas in the savanna region (Sokoto, Nguru, Yola and Bida) reached 30 °C in 1981–2009. Conversely, relative humidity generally decreased in the western region (except Yelwa and Sokoto) but increased in the east, reaching up to 5% increase at Jos and Potiskum.

Figure 8 shows that mean ET in most parts, except the west, and around Jos and Maiduguri, increased by less than 1 °C; in the Sahel (Nguru), it increased by



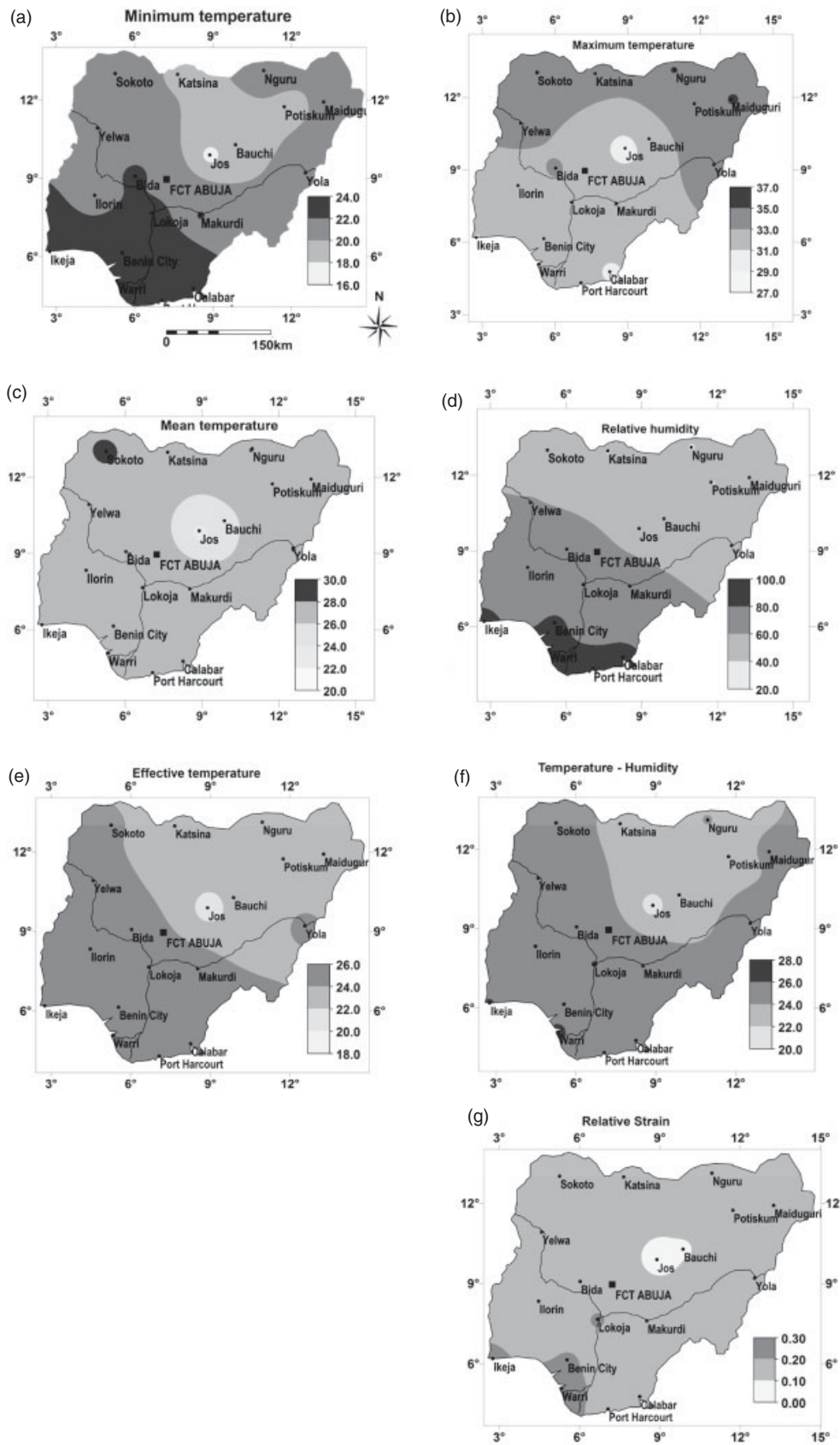


Figure 6. Mean distribution of temperature, relative humidity and thermal comfort indices (ET, THI and RSI) in 1951–2009 for Nigeria.

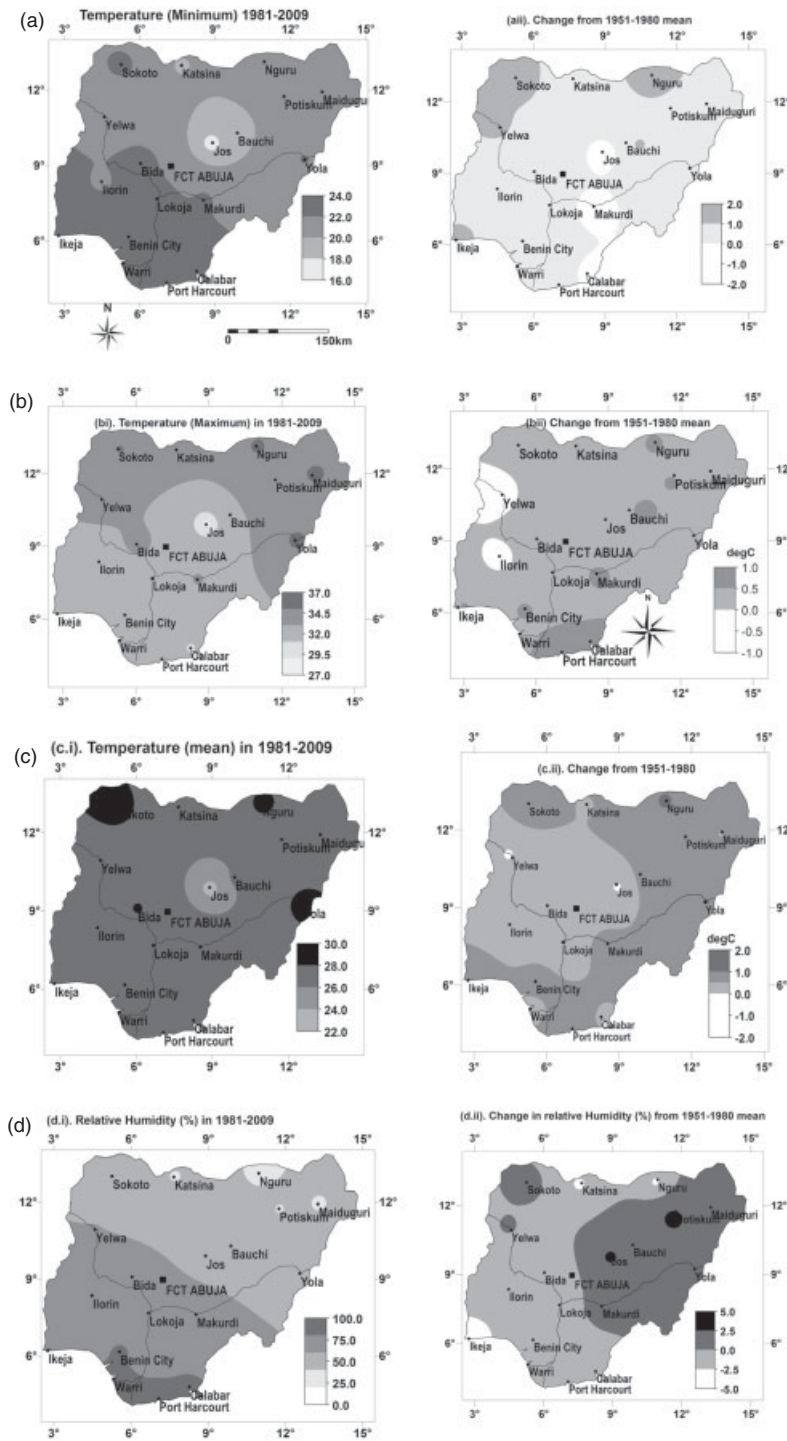


Figure 7. Temperatures and relative humidity in 1981–2009, and change relative to 1951–1980 means in Nigeria.

1–2 °C. Change in mean THI in 1981–2009 from 1951 to 1981 mean was similar to ET, with a less than 2 °C decrease in the west and montane region. Port Harcourt and Nguru in the tropical wet and sahel savanna, respectively, exhibited 1–2 °C increase in the mean THI. The result of RSI also shows that while Yola, and Benin City showed a decrease by about 0.04, and about 0.02 in the northwest and few other stations (Ilorin, Jos, Potiskum and Maiduguri), other parts of the country have showed increase, exceeding 0.04, near Benin City

in the southern region, and near Yola in the northeastern region.

### 3.3. Trends in temperature, relative humidity and thermal comfort indices

The results of linear regression analysis and their significance for each variable and at all the stations are presented in Tables 3 and 4. The general regression equation is 4

$$y = a + bx \tag{4}$$

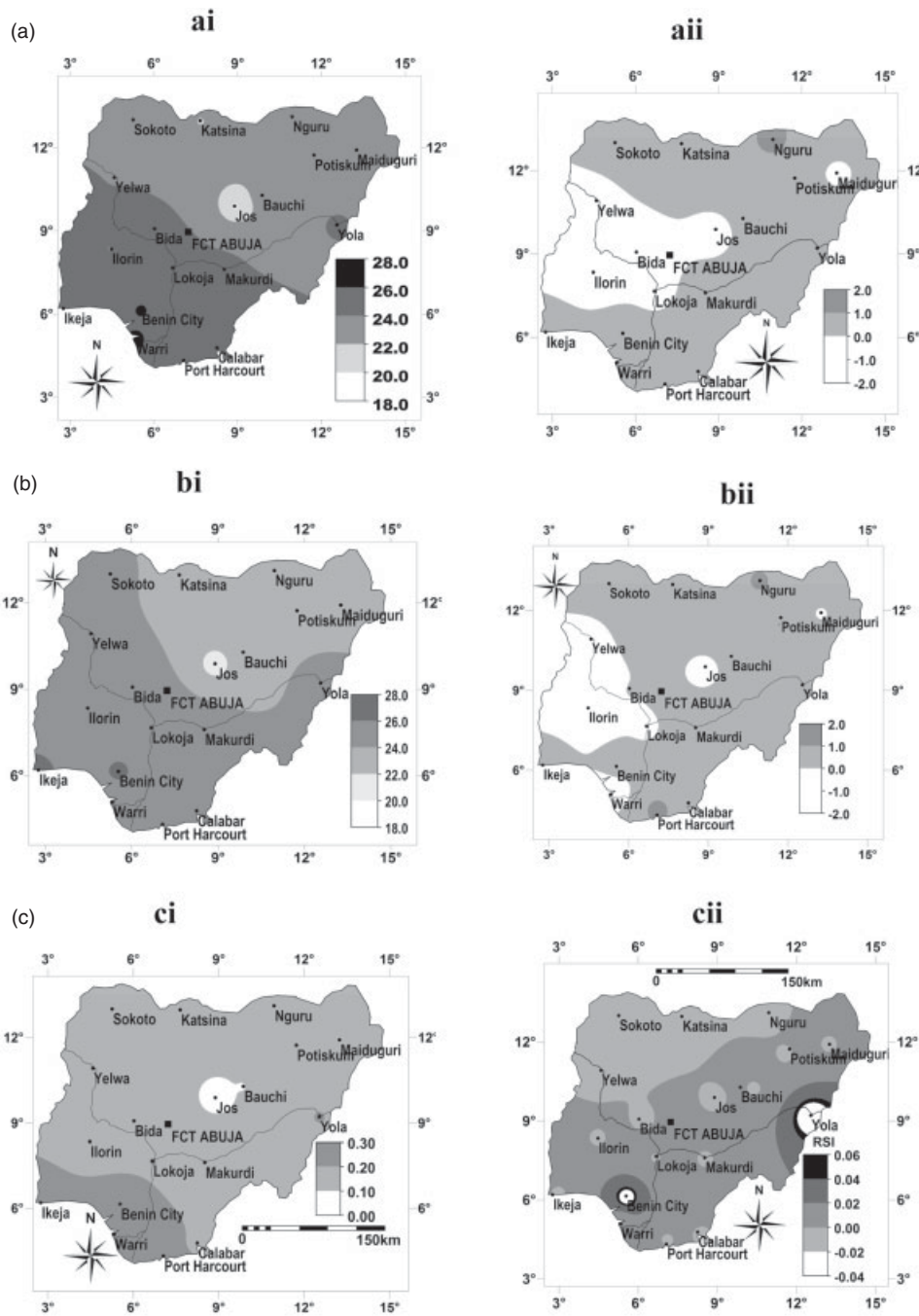


Figure 8. The ET, THI and RSI in 1981–2009, and relative to 1951–1980 means in Nigeria.

in which  $y$  is the dependent variable (ET, THI or RSI),  $x$  is the independent variable (time in years) and  $a$  (the constant) and  $b$  are fitting parameters. Parameter  $b$  is the regression coefficient quantifying the rate at which the temperature or other variable changes with time. The temperature variables showed significantly increasing trend at most stations, except the montane and few stations in the savanna. Only the minimum temperature decreased at the montane region ( $b = -0.03$ ;  $p < 0.05$ ) while maximum temperature at Yelwa has also decreased ( $b = -0.03$ ;  $p < 0.05$ ). Whereas temperatures increased steadily at most stations ( $b \leq 0.05$ ;  $p < 0.05$ ) relative humidity has generally decreased, especially

in the tropical rainforest region ( $b$  varies from  $-0.07$  to  $0.17$ ;  $p < 0.05$ ) (Table 3). At Bauchi in the Sudan savanna region, however, there was a significant increase ( $b = 0.17$ ;  $p < 0.05$ ) within the 59 years. Similarly, ET, THI and RSI showed an increased trend at most of the stations, especially within the Sudano–Sahelian savanna ( $b$  varies from  $0.001$  to  $0.06$ ) and tropical rainforest ( $b$  varies from  $0.02$  to  $0.03$ ) regions (Table 4).

### 3.4. Monthly variation in thermal climate indices in Nigeria

Figure 9 shows that the stations within the tropical savanna (Sahel and Sudan) and montane regions have

Table 3. Linear trends in temperature in selected stations in Nigeria

Climate region	Stations	Temperature (°C)			Relative humidity (%)
		Minimum	Maximum	Mean	
Tropical savanna (Sahel)	Nguru	19.98 + 0.04x*	34.67 + 0.02x	27.32 + 0.03x*	36.75 - 0.01x
Tropical savanna (Sudan)	Katsina	18.82 + 0.02x	33.11 + 0.02x*	25.97 + 0.02x*	41.65 + 0.1x
	Sokoto	20.38 + 0.01x*	34.6 + 0.02x*	27.47 + 0.03x*	40.76 + 0.06x
	Maiduguri	19.34 + 0.02x	35.04 + 0.01x	26.85 + 0.03x	42.81 - 0.09x
	Potiskum	18.45 + 0.04x*	33.42 + 0.03x*	25.95 + 0.03x*	40.76 - 0.04x
	Yelwa	20.96 + 0.01x	34.81 - 0.03x*	26.89 - 0.01x	60.02 + 0.03x
	Bauchi	17.82 + 0.04x*	32.17 + 0.02x*	24.99 + 0.03x*	41.97 + 0.17x*
	Yola	20.77 + 0.04x*	34.36 + 0.01x	27.56 + 0.02x*	53.99 + 0.04x
Montane	Jos	17.19 - 0.03x*	27.01 + 0.02x*	21.85 - 0.002x	44.72 + 0.16x
Tropical savanna (Guinea)	Bida	22.27 + 0.02x	33.05 + 0.02x*	22.66 + 0.02x*	66.76 - 0.09x
	Ilorin	20.42 + 0.03x*	32.74 - 0.02x	26.58 + 0.01x	75.99 - 0.05x
	Lokoja	22.45 + 0.01x*	32.59 + 0.02x*	27.52 + 0.01x*	72.44 - 0.07x*
	Makurdi	21.18 + 0.03x*	32.52 + 0.02x*	27.19 + 0.02x	71.55 - 0.05x
Tropical Wet and Dry	Ikeja	21.65 + 0.05x*	30.25 + 0.02x*	25.95 + 0.04x*	86.28 - 0.13x*
	Benin	22.63 + 0.01x*	30.68 + 0.02x*	26.26 + 0.03x*	84.87 - 0.03x*
	Calabar	21.79 + 0.04x*	29.96 + 0.02x*	26.29 + 0.02x*	86.55 - 0.04x*
Tropical Wet	Warri	22.39 + 0.03x*	31.16 + 0.01x*	26.77 + 0.02x*	84.85 - 0.03x*
	Port Harcourt	21.79 + 0.02x*	30.17 + 0.03x*	25.98 + 0.02x*	84.56 - 0.03x

Linear trend of the asterisked (\*) row is significant at the corresponding station within 95% confidence level ( $p \leq 0.05$ ); 'x' is in years.

Table 4. Linear trends in thermal comfort indices in selected stations in Nigeria.

Climate region	Stations	Effective temperature (°C)	Temperature-humidity index, THI (°C)	Relative strain index,
				RSI (no unit)
Tropical savanna (Sahel)	Nguru	21.46 + 0.06x*	22.64 + 0.05x*	0.17 + 0.0001x
Tropical savanna (Sudan)	Katsina	22.45 + 0.001x	25.11 + 0.005x	0.13 - 0.0003x
	Sokoto	23.44 + 0.03x*	24.27 + 0.033x*	0.15 + 0.001x*
	Maiduguri	23.49 + 0.0001x	24.27 + 0.003x	0.14 + 0.001x*
	Potiskum	20.70 + 0.06x*	21.71 + 0.05x*	0.04 + 0.003x
	Yelwa	24.90 - 0.01x	25.67 - 0.007x	0.21 - 0.0001x
	Bauchi	21.61 + 0.03x*	22.18 + 0.03x*	0.07 + 0.001x
	Yola	24.07 + 0.03x*	24.72 + 0.03x*	0.15 + 0.0002x*
Montane	Jos	19.31 + 0.003x	19.41 + 0.006x	0.01 + 0.0001x
Tropical savanna (Guinea)	Bida	25.64 - 0.01x	25.98 + 0.003x	0.22 + 0.0001x
	Ilorin	24.77 - 0.01x	25.12 - 0.006x*	0.17 + 0.0001x
	Lokoja	25.90 + 0.001x	26.27 + 0.003x	0.22 - 0.0001x
	Makurdi	25.59 - 0.006x	25.87 + 0.001x	0.21 + 0.0001x
Tropical wet and dry	Ikeja	24.59 + 0.03x*	25.26 + 0.03x*	0.16 + 0.002x*
	Benin	25.14 + 0.03x*	25.25 + 0.03x*	0.17 + 0.002x*
	Calabar	25.89 - 0.01x	25.98 - 0.002x	0.21 + 0.0001x
Tropical wet	Warri	25.62 + 0.02x*	25.82 + 0.02x*	0.20 + 0.001x*
	Port Harcourt	24.89 + 0.02x*	22.06 + 0.10x*	0.15 + 0.0001x*

Linear trend of the asterisked (\*) row is significant at the corresponding station within 95% confidence level ( $p \leq 0.05$ ); 'x' is in years.

similar patterns with the peak relative humidity in August after a increase from April, and a decline from September till March. Relative humidity in the Guinea savanna was high in most months, especially between March and December. The relative humidity during most months exceeded 40%, except for Bida in January. Stations within the tropical rainforest had high relative humidity throughout the year, exceeding 70% in all months. Temperature variables; minimum, maximum and mean temperature had similar patterns at all the stations, except for the variations in the periods of the peak among the stations from different regions. The times at which the temperature variables peaked increased with increasing latitude. For example, peaks of all the temperature

variables within the tropical rainforest occurred in February. For most stations in the Guinea savanna, the peaks occurred in March, whereas temperatures peaked in April at stations within the Sudan savanna. The peaks occurred in May in the Sahel savanna. In addition, the temperature variables appear to be more stable in the tropical rainforest and montane regions than in the savanna.

### 3.5. Seasonal variation

Figure 10 shows that, ET in most regions ranged between within 24 °C and 26 °C in the rainy season, except along Jos–Bauchi axis in the montane region, and Sokoto in the Sudan savanna. The ET at Jos and Bauchi was small, ranging between 20–22 °C and 22–24 °C, respectively.



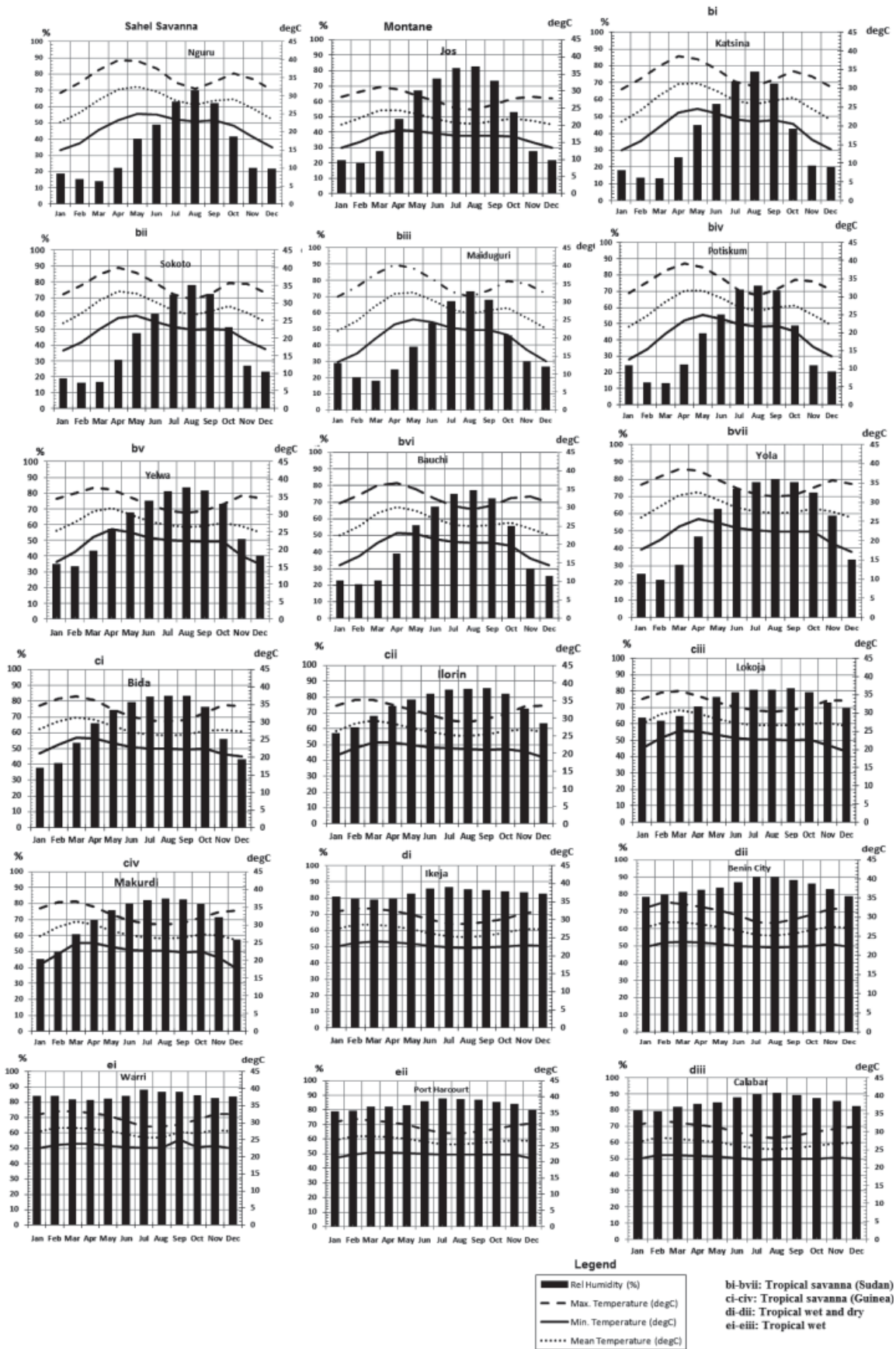


Figure 9. Mean monthly temperature and relative humidity at selected stations in different climate in Nigeria.



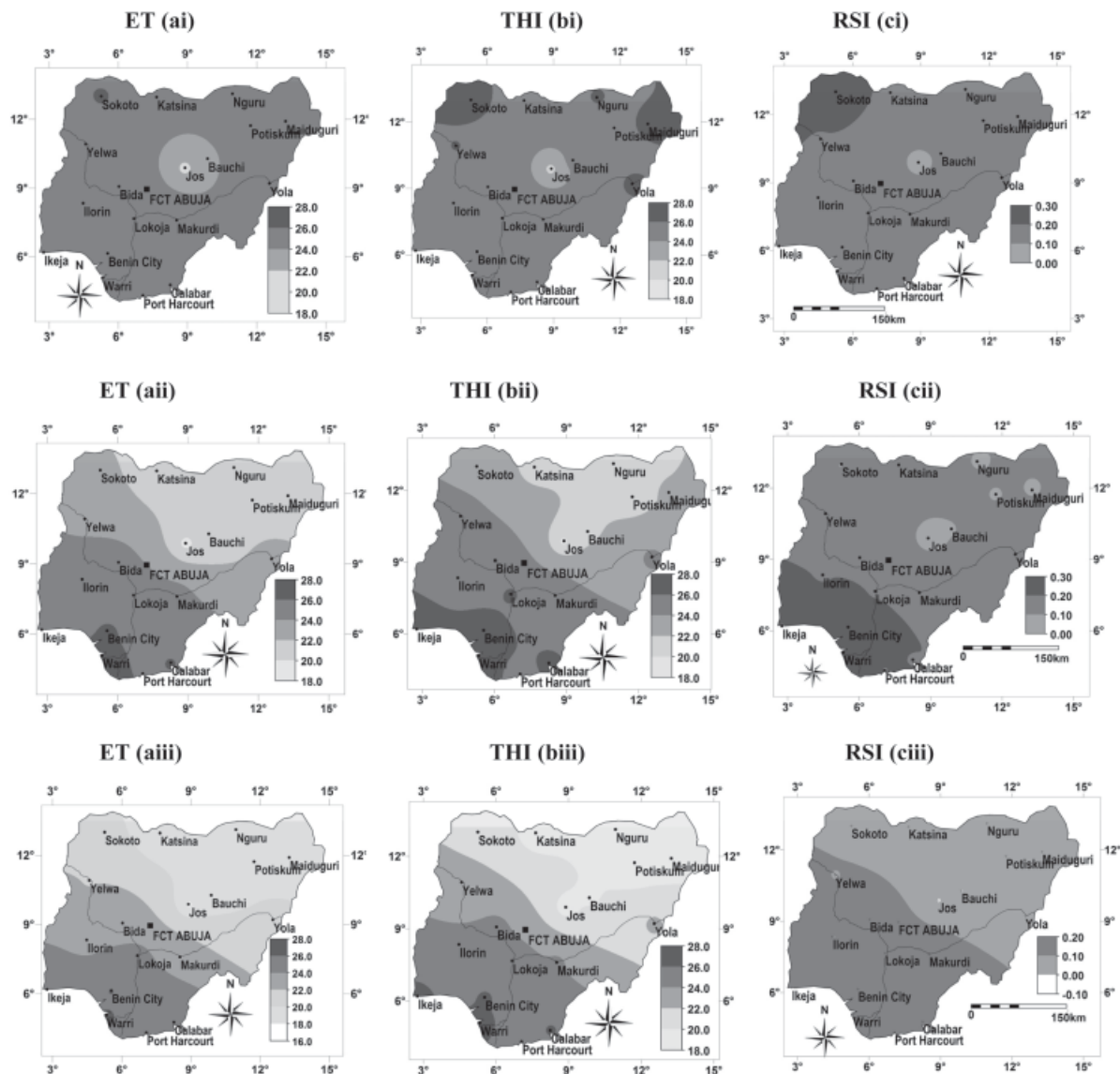


Figure 10. Mean (1951–2009) seasonal distribution of thermal comfort indices (ET, THI and RSI) in Nigeria.

Sokoto had the largest ET in the rainy season (26–28 °C). In the dry season, Benin, Warri and Calabar areas in the rainforest had larger ET (26–28 °C) than other regions. The ET during the dry season increased from the north to south. Jos, on the other hand, had a distinctly small ET in both rainy and dry seasons, except that the wet season's range (18–20 °C) was somewhat greater than in the dry season (20–22 °C). All stations in the savanna recorded smaller ET in the Harmattan than rainy and dry seasons, whereas most stations in the rainforest region had greater ET than the savanna and montane regions. The THI was also greater in the rainy season (20–28 °C) than in both the dry season and Harmattan period (18–28 °C) for most stations, but was smaller in the montane region than other regions in this season. Peak values occurred in the north during this season. In the dry season, the mean THI was smaller in the north than in the south. Only the montane region was relatively stable in both dry and rainy seasons. The THI during the Harmattan period

was much smaller for the savanna (excluding the Guinea savanna) regions and the northern stations in general. The influence of large THI also retreated from what it was in the dry season. A smaller RSI ratio also occurred in the Harmattan (–0.1 to 0.2) than other seasons (0 to 0.3). The RSI during the Harmattan period partitioned Nigeria into two major zones; the north with RSI ratio of 0 to 0.1 and south 0.1 to 0.2. The north-west had the largest RSI in the rainy season, whereas the largest RSI in the dry season occurred in the south west and Niger-Delta area.

### 3.6. Decadal variations

Figure 11(a) and (b) shows variations in the mean of ET and RSI in the decades from 1951–1960 to 2001–2010, and the forecasted patterns for 2011–2020 and 2021–2030. Only the ET and RSI results are presented. The pattern of the distribution of ET shows that thermal stress ( $ET \geq 25.6$  °C) began around Warri

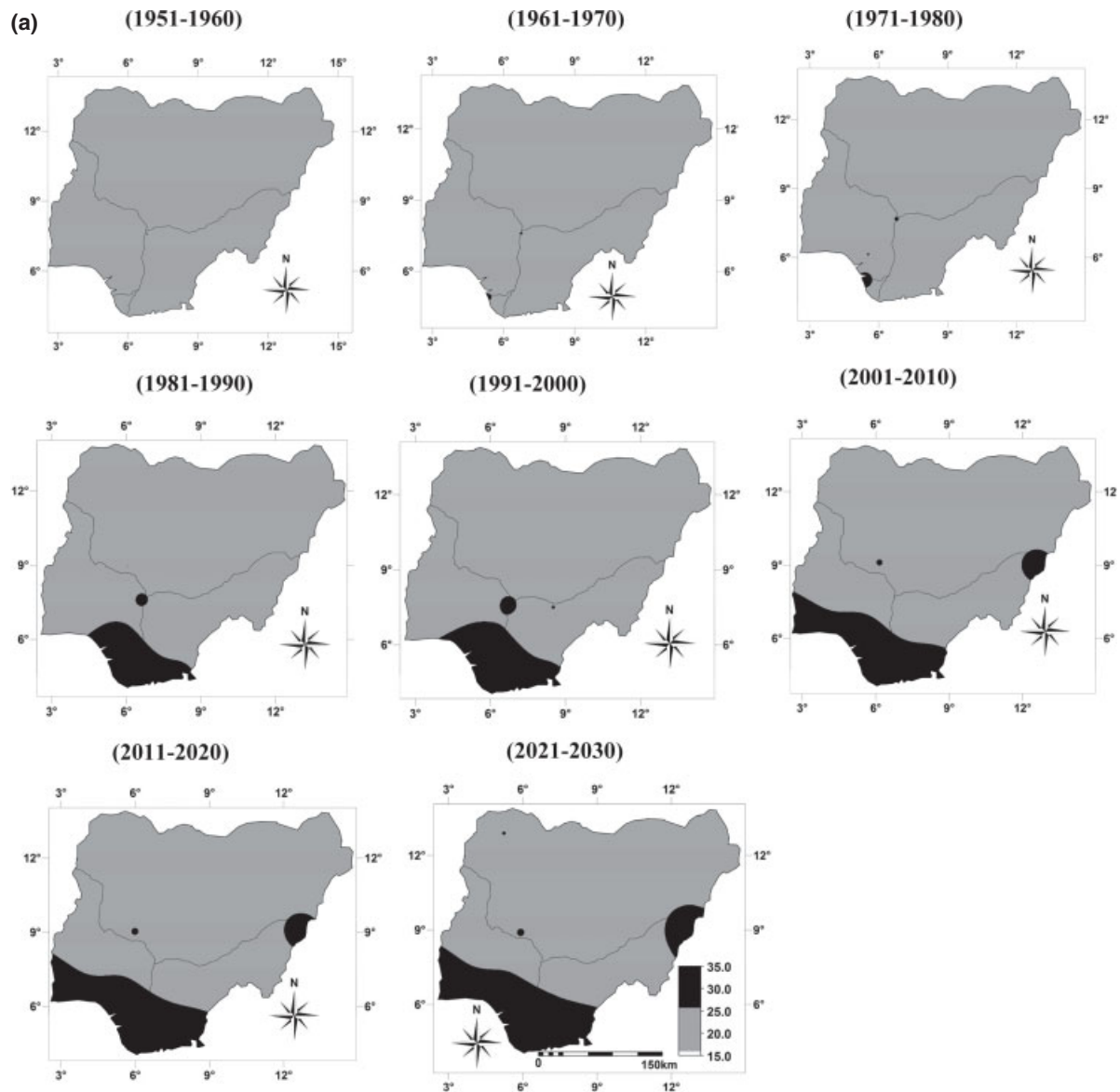


Figure 11. (a) Decadal variations in the distribution of thermal comfort and discomfort based on the mean effective temperature (ET) index for Nigeria, from observed (1951–1960, 1961–1970, 1971–1980, 1991–2000, 2001–2010) and projected (2011–2020 and 2021–2030) periods. (b) Decadal variations in the distribution of thermal comfort and discomfort based on the mean relative strain index (RSI) for Nigeria, from observed (1951–1960, 1961–1970, 1971–1980, 1991–2000, 2001–2010) and projected (2011–2020 and 2021–2030) periods.

and Lokoja in 1951–1960 and later spread to more regions in the south. By 1981–1990, most places in the Niger-Delta region had become thermally stressed, and the decade that began in 2001 showed an increase in thermal discomfort in the western region. The forecasted trend suggests a further increase northwards from the southwest and southeast, and from the northeast direction (Yola) towards the west.

The result of the RSI (Figure 11(b)), however, suggests a change from potential vulnerability to cold stress, to thermal stress in the northern region. The north-central part of Nigeria witnessed cold stress between 1951 and 1970, before such stress became restricted to the montane climate region in Jos from the decade starting in 1971. More regions have also become thermally uncomfortable from 1971, and the forecast suggests an increase from

both the west and east of the country, leaving only part of the north-central region and Ilorin (in the Guinea savanna) as thermally comfortable.

### 3.7. Delineation of regional thermal climate in Nigeria

Figure 12 shows the classification of Nigeria into zones of differing comfort and distress, based on a *k*-means clustering of the 59-year inventory of the mean annual values below or above comfort thresholds for each of ET, THI and RSI. All the indices (ET, THI and RSI) classified the north-central region, especially Jos–Bauchi region as having the ‘best’ thermal climate (i.e. Region 1). The Niger-Delta region was classified as the least comfortable zone by ET, the southwest, Niger–Benue confluence and east by THI and both east and west regions by

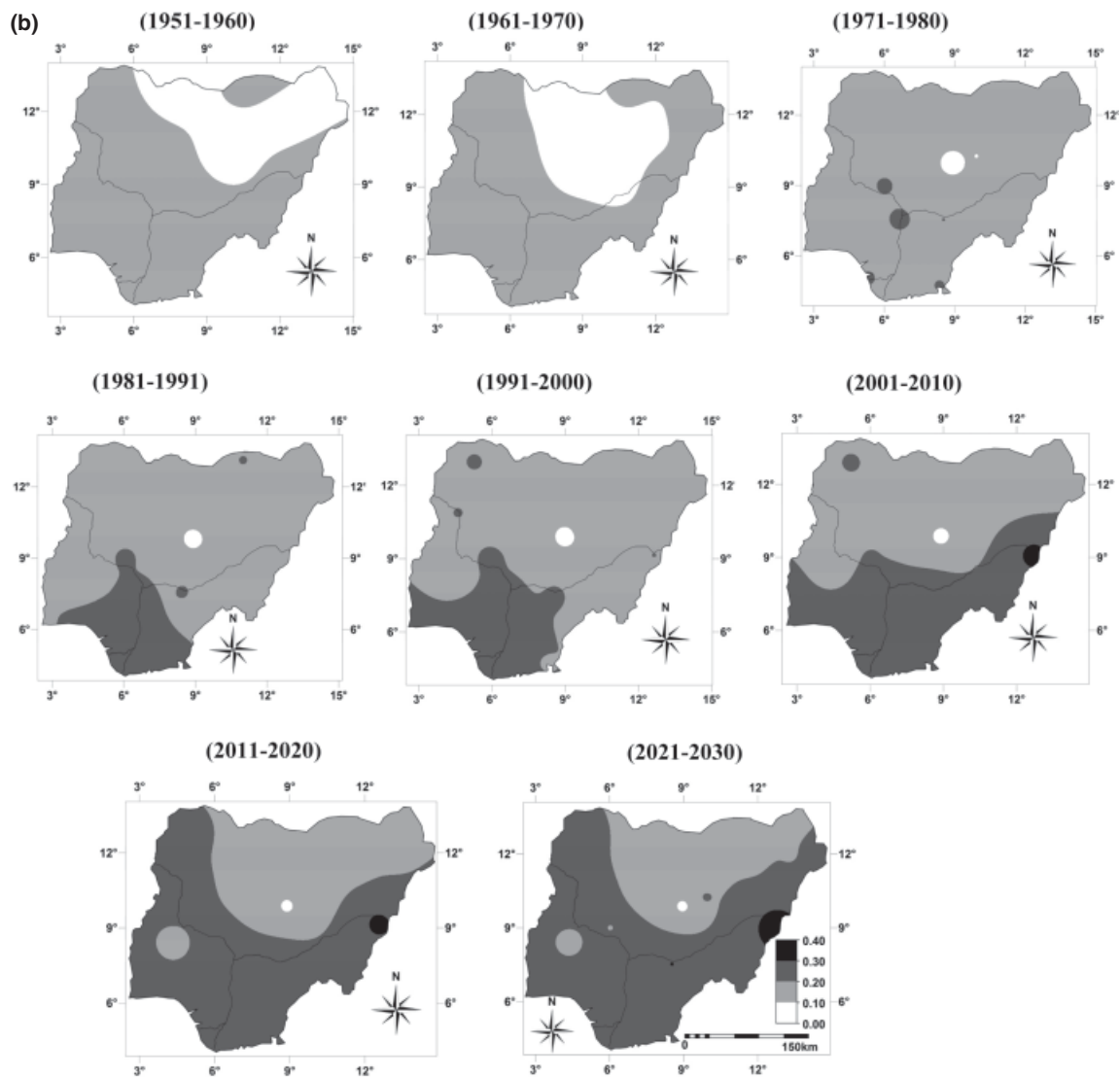


Figure 11. Continued.

RSI (Regions 4 and 5). Subsequently, the five regions identified are characterized as described below:

**Region 1:** This is the montane climate region. It apparently has the most comfortable physiologic climate in Nigeria. Both minimum and maximum temperatures are generally low ( $16\text{--}20\text{ }^{\circ}\text{C}$  and  $27\text{--}33\text{ }^{\circ}\text{C}$ ) and relative humidity is also moderate (about 50% on average). The altitude in this region is between 1200 and 1500 m. We found that Bauchi is also classified within the region. This is probably because the station has montane weather for most of the year.

**Region 2:** This comprises part of the western Nigeria and some of eastern Nigeria including parts of the Guinea, Sudan and Sahel savanna. Parts of the region experience thermal stress in dry season and early rainy season, but not in the Harmattan and rainy season. The thermal condition is seasonal.

**Region 3:** This comprises the highly urbanized and industrial regions, in which thermal stress in 1981–2009 was greater than previously in 1951–1980. Temperature

and relative humidity are high because the region is close to the Atlantic Ocean. Places within the region (as demonstrated by the meteorological data we used) have similar seasonal and monthly patterns in temperature, relative humidity and thermal condition. The thermal stress is likely to be partly man-made; a result of urbanization.

**Region 4:** This region includes the Niger-Delta in the south, and north-eastern Nigeria, most of which have been categorized as thermally stressed in the dry season and the Harmattan period. Studies (Ogundare and Sidiq, 2010) have shown that the thermal stress in part of the Niger-Delta region may be linked to the oil exploitation and gas flaring there. The classification of the north-eastern region is into this region is probably based on its high ( $35\text{--}37\text{ }^{\circ}\text{C}$ ) maximum temperature, which suggest significant daytime thermal stress.

**Region 5:** This is the most uncomfortable region in Nigeria, and comprises part of the Niger–Benue trough and part of the north east of the country. The

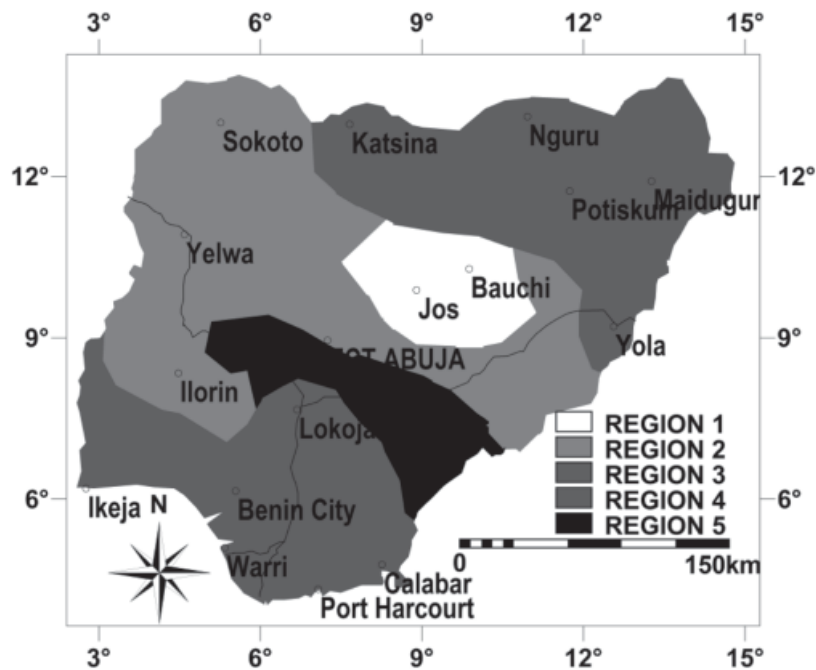


Figure 12. Nigerian regions based on thermal condition. Region 1 is most thermally comfortable while Region 5 is characterised with most thermally stressed condition, thermal stress increases from Regions 1–5.

Niger–Benue trough is the most uncomfortable in almost all the periods considered (e.g. dry, Harmattan and rainy season in 1951 to 2009 and 1981–2009).

#### 4. Discussion and conclusions

We have investigated the spatial and temporal variations in the thermal comfort of Nigeria, using both unitary (temperature and relative humidity) and integrative indices (ET, THI and RSI). The mean annual minimum, maximum and mean temperatures for 1951–2009 (with standard deviations in brackets) are 21.4 (3.5), 32.8 (3.4) and 27.1 (2.7) °C, respectively. The mean relative humidity was 62 (24.8) %. The mean ET, temperature–humidity index (THI) and relative strain index (RSI) are 24.3 (0.85), 24.8 (1.83) and 0.20 (0.18) °C, respectively. We found that ET, THI and RSI varied substantially over the whole of Nigeria, and we think that these variables merit further attention, especially to ascertain the uncertainties in their estimates. For example, while RSI indicated that the north central part of Nigeria had some cold stress in the years 1951–1970, the THI or ET did not. We also noticed differences in the relationship between temperature and relative humidity with ET, THI and RSI (Figure 13), which can explain the differences that were observed in the comfort indices that were investigated in this study. The different results of the ET, THI and RSI suggest that relying on only one index of thermal climate is not sufficient to interpret the Nigerian physiologic or thermal climate. This is probably partly because Nigeria is a large country and contains about six climate regions (as noted earlier in the study),

and is not as homogenous as in most countries where use of singular thermal index would produce less uncertainty.

The influence of relief on the climate of Nigeria is shown to be significant by the thermal comfort classification of Jos, the montane station as the ‘most’ thermally comfortable region in Nigeria. It is well known that temperature diminishes with increasing altitude. On the other hand, regions classified as thermally uncomfortable, the valleys of the Niger and Benue rivers, Niger-Delta region, southwest and northeastern Nigeria exhibit some contrasting features. Previous study (Ayoade, 1978) classified the Niger-Benue valley as the most uncomfortable climate region in Nigeria. The reason for this is not yet fully understood. Nonetheless, the location of the Niger-Benue valley places it at the front of the Inter Tropical Discontinuity (ITD) for more of the year than any other part of Nigeria. Further study will be required to understand the effect of its position on the thermal condition there. Studies of the Niger-Delta region (Ogundare and Sidiq, 2010) have implicated gas flaring activities associated with oil exploration as the main cause of rise in ET. Southwestern Nigeria has rapidly urbanized since colonial times (United Nations, 2004, 2012). Commerce and industry have grown and with them administration and the human population, and these have had their impacts on local climate with ‘heat islands’ in many of the towns (Omogbai, 1985, Aina, 1989, Oniarah, 1990, Adebayo, 1991, Efe, 2004, Adelekan, 2005, Akinbode *et al.*, 2008).

In addition, the comparison of the periods 1951–1980 and 1981–2009 and decadal means of the three thermal indices (ET, THI and RSI), showed significant increase in the area that experiences thermal distress with increasing time. The projected figures suggest that heat stress will



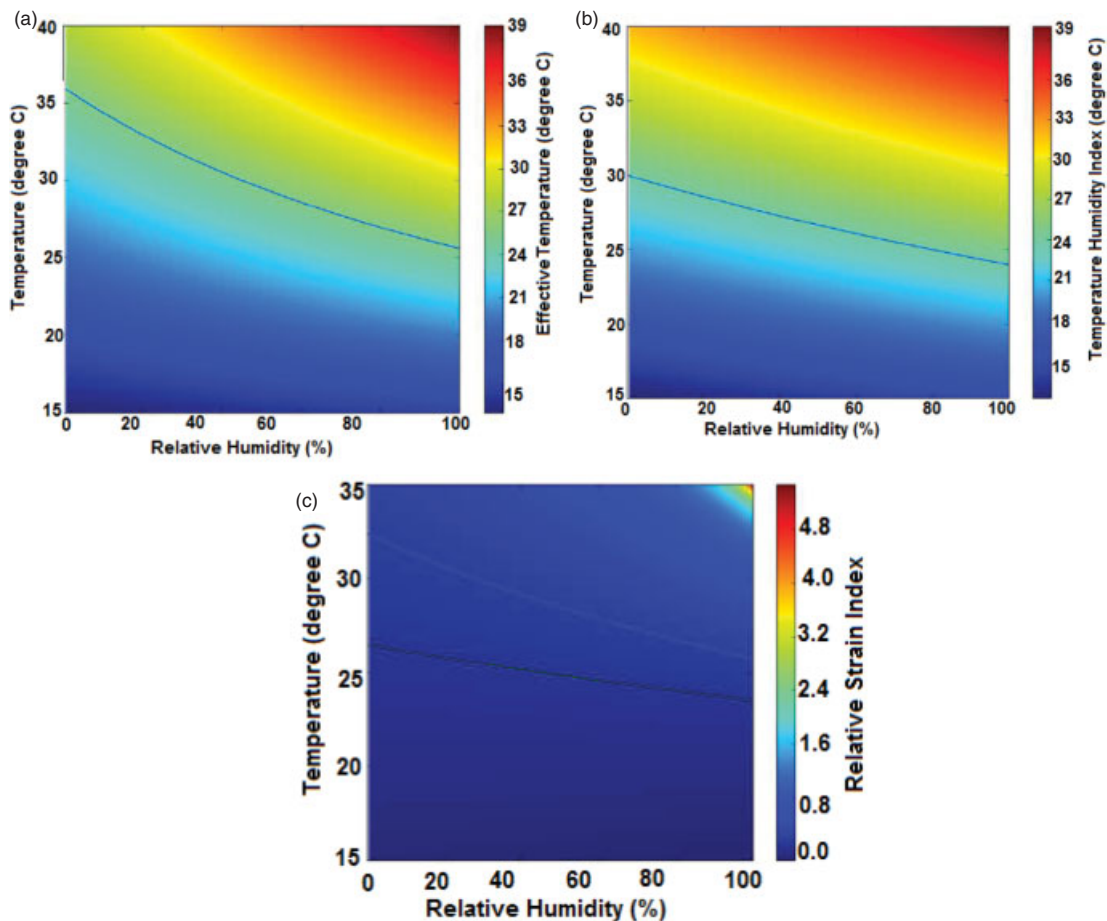


Figure 13. Effective temperature (a), temperature-humidity (b), and relative strain (c) indices over different ranges of temperature and relative humidity in Nigeria. The curves shown are thresholds (25.6 °C, 24 °C and 0.1 for ET, THI and RSI, respectively). Figure 13(c) shows only when RSI value is positive, and does not include extreme or negative units when the interpretation of RSI can be ambiguous.

be experienced at almost everywhere except the north central region within the next two decades. The monthly patterns showed that thermal stress is first experienced in the rainforest region before the northern region, in a trend that is similar to the movement of the ITD. The seasonal distribution of the thermal condition showed that more areas experienced thermal stress in the north in the rainy season while during the dry season, more areas experience thermal stress in the south. Large areas in the north were more comfortable in the Harmattan. Of the three seasons, Harmattan was observed to be the most comfortable in the north of Nigeria, although the Harmattan period is characterized by dust which is a more serious hazard than heat at this time.

In conclusion, we can accept the first hypothesis that thermal stress has increased in Nigeria between 1951 and 2009 but not the second which states that thermal comfort is directly related to proximity to either the influence of the Atlantic Ocean or Sahara. On the other hand, except on the highland at Jos (1285 m) and the uncertain influence of the movement of the Inter Tropical Discontinuity (ITD), more studies will be required to distinguish the role of urbanization and movement of the air masses on the thermal comfort in Nigeria.

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