SPATIO-TEMPORAL VARIATIONS OF HEAT WAVE CHARACTERISTICS IN DIFFERENT CLIMATIC ZONES OF NIGERIA

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MTech/SPS/2015/6068

WEST AFRICAN SCIENCE SERVICE CENTRE ON CLIMATE CHANGE AND ADAPTED LAND USE (WASCAL) FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA NIGERIA

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THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA, NIGERIA, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF TECHNOLOGY (MTECH) IN CLIMATE CHANGE AND ADAPTED LAND USE

MARCH, 2018

DECLARATION

I hereby declare that this thesis, titled "**Spatio-Temporal Variations of Heat Wave Characteristics in Different Climatic Zones of Nigeria**", is a collection of my original research work and it has not been presented for any other qualification anywhere. Information from other sources (published or unpublished) has been duly acknowledged.

RAGATOA, Dakéga Saberma ………………………

MTech/SPS/2015/6068 SIGNATURE / DATE

FEDERAL UNIVERSITY OF TECHNOLOGY

MINNA, NIGERIA.

CERTIFICATION

The thesis titled: "**Spatio-Temporal Variations of Heat Wave Characteristics in Different Climatic Zones of Nigeria**" by RAGATOA Dakéga Saberma (MTech/SPS/2015/6068) meets the regulations governing the award of the degree of Master of Technology (MTech) of the Federal University of Technology, Minna and it is approved for its contribution to scientific knowledge and literary presentation.

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Dean, Postgraduate School	Signature & Date

DEDICATION

I dedicate this research work to God the creator and Master of all.

I dedicate also this work to my family, especially my father and my loving mother who passed away.

"***Blessed are all who fear the LORD and live his way***".

Psalm 128:1

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ABSTRACT

African countries are highly vulnerable to climate change, especially climate extremes. Heat Waves (HW) (prolonged extreme heat over an area) are projected to become very long and more intense in the upcoming decades and will therefore seriously affect health, infrastructures and especially agriculture that is the main economic activity. This study investigates the heat wave characteristics in different climatic zones in Nigeria over a long period considering the present and the future temperature conditions. The objectives were specified to: analyse the temperature trend in Nigeria, analyse HWs occurrence from 1981 to 2016 in the different climatic zones (Coastal, Tropical Rainforest, Guinea Savannah, Sudan Savannah and the Sahel) in Nigeria, predict the future aspects of HWs to projected 2100 and evaluate the future trend of HW characteristics. ERA-INTERIM reanalysis daily minimum and maximum temperature data from 1981 to 2016 were collected from ECMWF data base and used as the present time. Observation data, 17 stations data were also obtained from NiMet across the country. CORDEX-AFRICA Weather Research and Forecast (WRF) model outputs from 2018 to 2100 were obtained with the same parameters from GSP WACS, F.U.T Akure under RCP4.5 and RCP8.5. Five heat wave characteristics were studied, namely the heat wave number (HWN), duration (HWD), frequency (HWF), amplitude (HWA) and magnitude (HWM) using four definitions: TX90 and TN90 that are temperature based 90th percentile thresholds; Excess Heat Factor (EHF); and the Heat Waves Magnitude Index daily (HWMId). The trend analysis was performed on the observed daily minimum and maximum temperature for the 17 stations. The Modified Mann-Kendall trend test was performed because of the serial correlation in the data, and the results showed significant increasing and significant decreasing trends. The slope was very low in many stations. The study of HW characteristics in different climatic zones revealed that from 1981 to 2016, HWs occurred and covered more zones in the last decades. The Sahel was really affected by the highest number of events and the highest number of days for the duration and the frequency. The HWMId was used to quantify the intensity of HWs in the present time and revealed super extreme HWs in the Sahel and extreme HWs in the South. The prediction using WRF under the two scenarios RCP4.5 and RCP8.5 has shown an aerial increase in the frequency and magnitude of HWs all over the period under consideration. In the 2050s, there will be spatial increase and also an increase in the duration of HWs in almost all the Nigerian land. Even the Coastal zone will be having super extreme (HWMId >= 32) HWs. The RCP8.5 revealed more dramatic and dreadful HWs from 2073. The trend of each of the characteristics using the different definitions under the two scenarios from 1981-2100 revealed significant trends (p-value < 0.05) of many zones and the magnitude of the trends (Sen's slope) was revealed to be positively very low for some characteristics using some definitions and high (3.5) for other characteristics. Similarly, there are also negative slopes (-0.03). This study could help in agricultural decisions based on climatic zones and also in the infrastructures adjustments and mainly health domain considering that HWs will be more frequent and more intense in the near future time.

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LIST OF ABBREVIATIONS AND ACRONYMS

AT	Apparent Temperature
AAT	Annual Aggregated Time series
AFWA	Air Force Weather Agency
ASCII	American Standard Code for Information Interchange
AU	African Union
CC	Climate Change
CCl	Commission for Climatology
CCSP	U.S. Climate Change Science Program
CDC	Centres for Disease Control and Prevention
CDO	Climate Data Operators
CE	Climate Event
CEW	Climate Extreme Weather
CORDEX	Coordinated Regional climate Downscaling Experiment
CWDI	Cold Wave Duration Index
DTR	Diurnal Temperature Range
ECMWF	European Centre for Medium-Range Weather Forecasts
EHF	Excess Heat Factor
EHI	Excess heat indices
EHI(accl)	Acclimatisation to heat
EHI(sig)	Climatological significance
EPA	U.S. Environmental Protection Agency
ET	Expert Team
ET-CRSCI	Expert Team on Climate Risk and Sector-specific Climate Indices
ET-SCI	Expert Team on Sector Specific Climate Indices
ETCCDI	Expert Team on Climate Change Detection and Indices
EWD	Extreme Weather Disasters
FAA	Federal Aviation Administration
FSL	Forecast Systems Laboratory
FUTA	Federal University of Technology Akure
GCM	Global Climate Models
GSOD	Global Surface Summary of the Day
HD	Hot Day
HW	Heat wave
HWA	Heat Wave Amplitude
HWD	Heat Waves Duration
HWDI	Heat Wave Duration Index
HWF	Heat Waves Frequency
HWMI	Heat Wave Magnitude
HWMI	Heat Waves Magnitude Index
HWMId	Heat Waves Magnitude Index daily

$HWMId_{tn}$	Minimum Temperature Heat Wave Magnitude Index daily
$HWMId_{tx}$	Maximum Temperature Heat Wave Magnitude Index daily
HWN	Heat Wave Number
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-tropical Convergence Zone
ITD	Inter-tropical Discontinuity
JCOMM	Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology
LOESS	Locally Weighted Smoothing
LOWESS	Locally Weighted Scatter-plot Smoothing
MK	Mann-Kendall
MMK	Modified Mann-Kendall
NCAR	National Centre for Atmospheric Research
NCEP	National Center for Environmental prediction
NCO	NetCDF Operators
NetCDF	Network Common Data Form
NiMET	Nigerian Meteorological Agency
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
OU	University of Oklahoma
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
SD	Statistical downscaling
TM	Daily mean temperature
TMAX/TX	Maximum Temperature
TMIN/TN	Minimum Temperature
TN90	Days when TN > 90^{th} percentile
TNx	The Hottest Nights
TS	Time Series
TX90	Days when TX > 90^{th} percentile
TXx	The Hottest days
UWSP	University of Wisconsin–Stevens Point
WASCAL	West African Science Service Centre on Climate Change and Adapted Land Use
WCRP	World Climate Research Programme
WMO	World Meteorological Organisation
WRF	Weather Research and Forecasting
WSDI	Warm Spell Duration Index

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the study

Facts have shown that climate change (CC) is a reality that affect people differently in different communities and areas. It is obvious today that the weather is becoming hotter and hotter. The global average temperature has been on the increase since 1850 with the industrial revolution, but this became more intense from 1995. The 0.85 °C^2 temperature linear trend of the 1980 to 2012 century is higher than the 0.75 °C^2 related trend of 1906 to 2005 (Intergovernmental Panel on Climate Change (IPCC), 2014). This rapid increase in the surface temperature affects all the different interrelated parameters of the climate system causing a general worldwide concern (IPCC, 2007). The sea level is rising at a considerable rate submerging lands and ecosystems. The shifting of seasons and change in precipitation rate are all evidences of CC. The observed decrease of snow since 1978 in the Arctic sea with imagery provided by satellite is also an evidence of the changing climate. Mountain glaciers in hemispheres are decreasing because of the increasing heat. Many of human activities are affected by the observed changes in the climate like in Agriculture and health (IPCC, 2014).

The National Oceanic and Atmospheric Administration (NOAA) (2007), considered CC as a long-term shift in the weather statistics (using averages). For instance, it could be taken as a change in climate normals that is the temperature and precipitation average values over 30 years or more of the considered area. The variability in the climate is naturally driven by the interactions of the system atmosphere-earth-ocean associated with changes in the amount of solar radiation reaching the different places of the earth. Evidences of CC in Africa, considering anthropogenic activities, have increased. Analyses of decadal (10 years) temperatures powerfully show a continual increased warming trend across the continent over the last 50 to 100 years (Niang *et al.*, 2014).

The most confusing and impactful consequences of CC are extreme events. Extreme events or extreme weather are not well-known even though great advances of the scientific knowledge about climate evolution have been made during these last decades. The changes in the climate implies changes in the spatial extent, frequency, intensity, duration, and the time frame of climate events and can lead to ground-breaking extreme weather and climate events (IPCC, 2012). CC is a dynamic phenomenon, with the known impacts undergoing changing, some are worsening and hence appear to be newly discovered. It has become evident that extreme events destroy properties, injure or kill people, and menace endangered species according to the Centre for Disease Control and Prevention (CDC) (2013). Climate Extreme Weather (CEW) and Climate Events (CE) have significant impingement on societies in their efforts to cope/adapt to a changing climate and are among the most serious challenges (U.S Climate Change Science Program (CCSP), 2008). The environmental consequences of CC, both those already observed like temperature extremes, precipitation extremes, drought, storms and the anticipated ones, such as sea-level rise, Heat Waves (HWs), more strong hurricanes, and demeaned air quality, will instantly and ulteriorly affect human health. Increases in the frequency and severity of regional HWs for instance, have the potential to harm many people (Vellinga, 2015). Climate extreme events are more and more rising in the scientific world. To understand the climate extremes, there is a need to analyse them one after the other in their causes and manifestations.

Therefore, to understand very well the aspects/characteristics of CC and to be able to fore-prepare the effect, good, reliable models and prediction tools are used nowadays. HWs are aspects of climate extremes and their impacts are felt world over especially around the tropics (direct hit of sunshine) where the West Africa countries are located. These impacts are also felt by humans, infrastructures and crops (Soja and Soja, 2003; Jones and Thornton, 2003; Barnabás *et al.*, 2008; Le, 2010; Lobell and David, 2010; Lobell *et al.*, 2011; Luo, 2011; Ajetomobi, 2015; Ajetomobi, 2016; Massetti and Mendelsohn, 2016; Zhang, *et al.*, 2017) and hence poses a great challenge for West African countries that rely mainly on agriculture. It is therefore expedient to understand the patterns of HWs and also be able to predict this phenomenon in the most affected areas. Researches have been conducted in this area of study, however, they are still very few especially at a regional scale in Africa. By increasing the knowledge and by predicting the regional impacts, communities will be able to come forth to develop specific adaptation measures and apply adequate mitigation practices. An assessment of the present and future occurrence of HWs is needed to tackle the related impacts.

1.2 Statement of the Research Problem

Africa is considered in climate issues as one of the highly defenceless continent to weather and climate variability according to Russo *et al.* (2015) and Ceccherini *et al.* (2016a). The challenges countries are facing because of CC are numerous and Africa is the most affected. The lack of knowledge about the present and future patterns of the changing climate makes it difficult to handle. In West Africa for example, the living conditions can be greatly improved if taking into account CC different extreme impacts. Another instance is that recently, studies showed with satellite time series imagery that yield exposure would be caused by HWs via plant harm and stifled crop growth and even when a slight increase in the mean temperature above the optimal temperature for the culture is observed as noticed Gusso *et al.* (2014). Lesk *et al.* (2016) highlighted the importance of historical outcomes of Extreme Weather Disasters (EWDs) on agricultural production for example, and stresses on the urgency with which the world cereal production system should adapt to CEW and CE in a changing climate. Unfortunately, study has shown that Africa has not only experienced hotter, more tenacious and more extended HWs than in the last two decades of the last century but also, 50 % of regional climate projections in the future imply that HWs that are extraordinary nowadays will go on regularly by 2040 (Russo *et al*., 2016). There is need to assess the spatio-temporal behaviour of HWs in order to know the patterns and to predict the occurrences as this will enhance communities awareness and decision-making toward the reduction of disaster risks and increase adaptation strategies; this will help to improve on assailable farming systems' protection and their dependent populations.

1.3 Aim and Objectives

The aim of this research work was to investigate the spatio-temporal variations of HWs characteristics (HW number, duration, frequency, amplitude and magnitude) over different climatic zones in Nigeria. The specific objectives that were defined in the work were to:

(i) analyse the temperature trend in Nigeria;

(ii) analyse HWs occurrence from 1981 to 2016 in five climatic zones (Coastal, Tropical Rainforest, Guinea Savannah, Sudan Savannah and Sahel) in Nigeria;

(iii) predict the future aspects of HWs to 2100; and

(iv) evaluate the future trend of HW characteristics.

1.4 Research Questions

There is need for an increased knowledge on HWs in Nigeria, due to the adverse effects of HWs in various domain of human activity. This gap needs to be filled, and for this to be achieved, these following questions should be tackled:

(i) What is the temperature trend of Nigeria ?

(ii) How do HWs occur in the different climatic zones in Nigeria?

(iii) What are the patterns of HW characteristics in the coming years?

(iv) What will be the future trend of each aspect of HW in Nigeria?

1.5 Justification of the Study

Extreme events, (droughts and HWs) cause enormous damage to food production all over the world and especially in Africa and South Asia (Lobell *et al.,* 2011, 2012, 2013). HWs have always been the cause of high damages to crop yields, to infrastructure and also to health. They are projected to increase under CC and have serious negative implications to infrastructures, health and food production and security (Dosio, 2016; Russo *et al.*, 2016). The threat of HWs on crop yields especially is a challenge in African countries because of their almost total dependence on agriculture. Therefore, understanding the characteristics/aspects of HWs and their trend in the future is an important step towards estimating and unravelling the threats posed by HWs. The knowledge thereof will enhance farmers' coping capacity, improve agricultural policies and increase the resilience of rural communities towards both today and future climate extreme events.

Research on HWs present and future characteristics is therefore important, as this will provide with a Regional Climate Model (RCM) projected outputs, an accurate knowledge on HWs in Nigerian climatic zones and help in agricultural production in each of the climatic zones of the study area. Doing a sound analysis on the evolution of HWs in the future will help many of vulnerable communities in Nigeria to develop adaptive strategies to the dreadful future HWs. The results of this study are valuable for people and researchers in farming and agriculture, in the engineering industry and for health experts as well as related software providers in developing better practice and tools for HWs and decision makers in adaptation strategies.

1.6 Scope and Limitation of the Study

This study focuses on the characteristics of HWs in different climatic zones (Coastal, Tropical Rainforest, Guinea Savannah, Sudan Savannah and the Sahel) in the Federal Republic of Nigeria. The research analysed HWs from 1981 to 2016 as present time and projected from 2018 to 2100 the characteristics of the phenomenon. The World Meteorological Organization (WMO) Expert Team on Climate Change Detection and Indices (ETCCDI) and the Expert Team on Climate Risk and Sector-specific Climate Indices (ET-CRSCI) called today the Expert Team on Sector Specific Climate Indices (ET-SCI) project indices were used with the extra index (the Heat Waves Magnitude Index daily (HWMId)) to look at the occurrence and aspects of HWs. The Weather Research and Forecasting (WRF) model outputs from the COordinated Regional climate Downscaling EXperiment (CORDEX) runs were used under the Representative Concentration Pathway 4.5 (RCP4.5) and the Representative Concentration Pathway 8.5 (RCP8.5) for HW prediction in Nigeria.

1.7 Description of the Study Area

The area of the study covers Nigeria, one of the biggest countries in West Africa in terms of land area and population. The country covers a land area of approximately 923,769 square kilometres (km^2), (with 909,890 km^2 of land area and 13,879 km^2 of water area) (National Bureau of Statistics, 2013). Nigeria, in West Africa, covers 5 climatic zones, namely the Coastal, Tropical Rainforest, Guinea Savannah, Sudan Savannah and the Sahel, and this is an important aspect of the study. This section gives important details about the location and also have clear look on the climate of Nigeria.

1.7.1 Location and extent of Nigeria

Nigeria is found on the West coast of Africa, and lies on 4°-14° latitude North (of the Equator) and 2°2’-14°30’ longitude East (Federal Ministry of Environment of Nigeria, 2009) as shown in the Figure 1.1. On the West of Nigeria is the Republic of Benin, the Eastern side border with the Republic of Cameroon; the North with Niger Republic and Chad Republics and on the South is the Gulf of Guinea. From East to West the distance in Nigeria is about 767 km, and from North to South 1,605 km. Approximately 35 % of the land extent is arable, 15 % is considered to be used for pastures, 10 % for forest reserve, 10 % as residential and the leftover 30 % is considered uncultivable (Federal Ministry of Environment of Nigeria, 2009; National Bureau of Statistics, 2011).

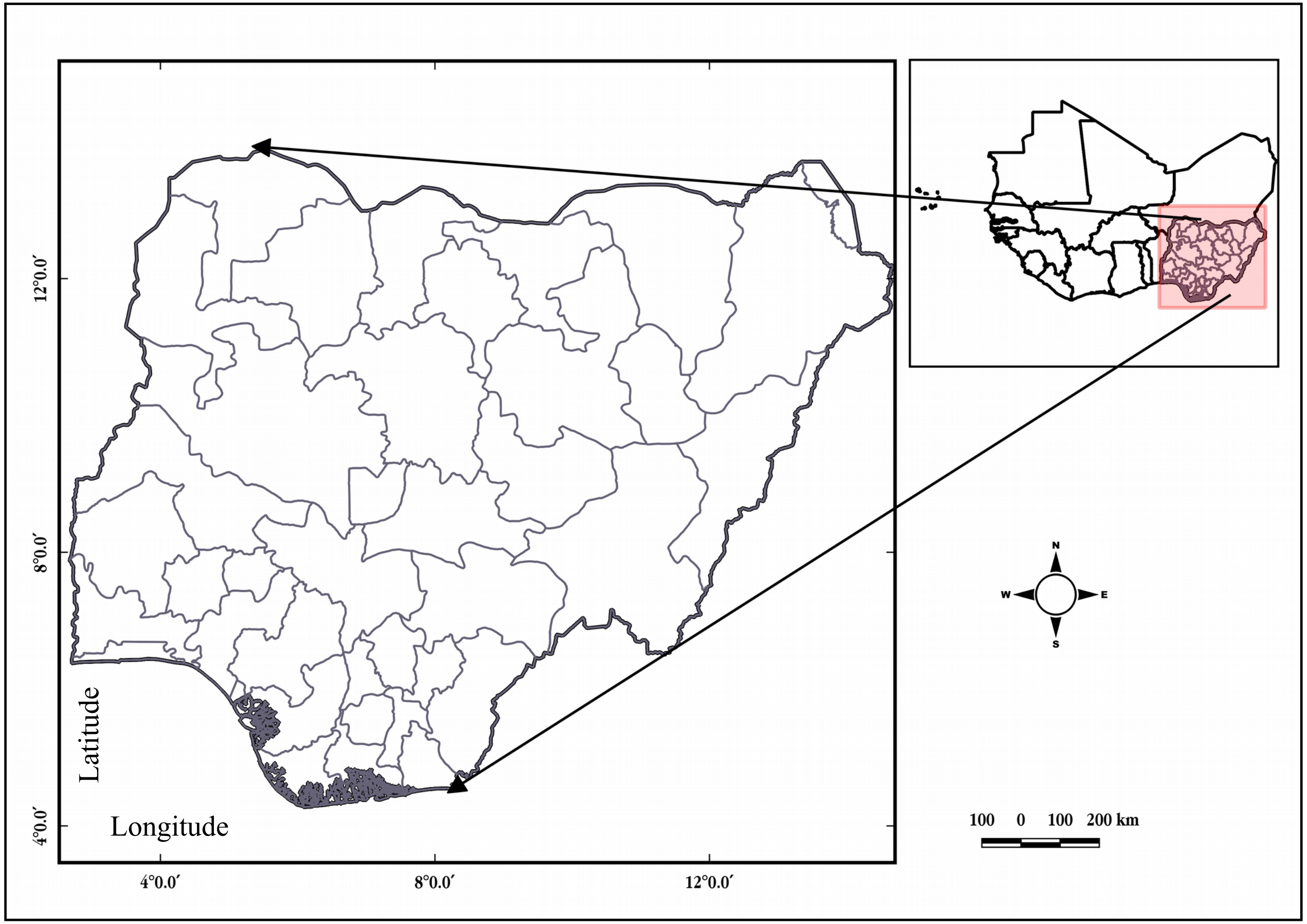

Figure 1.1: Study Area, Nigeria

1.7.2 Climate of Nigeria

Nigeria is covered by a tropical climatic condition that can be qualified as warm and the temperature is relatively high almost all the year with two seasons, the dry and wet season. The climate is influenced by the fundamental interaction of the warm and moist tropical marine air mass which comes from the Atlantic Ocean with the South West winds and the cool and dry tropical continental air mass coming from the Sahara Desert which is coupled with the dry, cool and dusty North East trades (Harmattan). The convergence area for the two air masses is the Inter-tropical Discontinuity (ITD). The ITD moves North and South bringing rainfall or dryness according to the seasons to different areas of the country. The Northbound of the ITD brings rain to all areas South of its location (rainy season), while the Southbound brings dryness (dry season) to areas in the North of the ITD. In general, the extreme South end of the country barely see dry season, while the wet season scarcely lasts more than three months in the North East of the country. Annual precipitation totals orbit around 2,500 mm Southbound to less than 400 mm Northbound (Federal Ministry of Environment of Nigeria, 2009).

The climate in Nigeria is characterised by strong latitudinal zones as mostly of West Africa, becoming progressively drier Northward. Rainfall and temperature are the important parameters and there is a clear sequence of wet and dry seasons in most areas. Topographic relief in the Plateau of Jos and along the Eastern play a significant role on local climate. In the extreme South and South Eastern parts of the country, the rainy season normally starts in February or March as the South West monsoon (moist Atlantic air), occupies the territory. The rains ordinarily start by strong and heavy winds but with scattered squalls. The confused quality of the storm rainfall is especially perceptible in the North during dry years. By April or early May in most years, the rainy season is already starting throughout most of the area South of the Niger and Benue river valleys. Farther in the North, it is usually in June-July that the rains really commence. The off-peak of the rainy season happen in most of Northern Nigeria in August, when air from the Atlantic cover-up the entire country. In Southern regions, this period states the August dip in precipitation. Although barely completely dry, this dip, especially marked in the South West, can be useful for agriculture, because it permits a little dry period for grain harvesting. From September through November, the North East trade winds generally bring a season of clear skies, moderate temperatures, and lower humidity for most of the country. From December through February, however, the North East trade winds blow powerfully and often bring with them plenty fine dust from the Sahara. These dust-laden winds, known locally as the Harmattan, often appears as a dense fog and cover-up everything with fine particles (National Bureau of Statistics, 2012).

The Harmattan is ordinary in the North but affects the entire country except for a constricting piece along the South West coast. An occasional strong Harmattan, however, can sweep as far Southern zone of the country, providing alleviation from high humidities and pushing clouds of dust out to the sea. Moving North from Ibadan, mean annual rainfall in the West North of Kaduna, through the Northern Guinea Savannah and then the Sudan Savannah zones, the total rainfall and the length of the rainy season decline steadily. The Guinea Savannah starts in the middle belt, or Southern part of Northern Nigeria. It is distinguished from the Sudan Savannah because it has more trees whereas the Sudan few trees and rainy seasons decline correspondingly in length as one moves Northwards. The regularity of drought periods has been among the most notable aspects of Nigeria climate in recent years, particularly in the drier regions in the North.

The twentieth century has been among the driest periods of the last several centuries; the well advertised droughts of the 1970s and 1980s were only the latest of several significant such episodes to affect West Africa in this century. At least two of these droughts have severely affected large areas of Northern Nigeria and the Sahel. These drought periods are indications of the great variability of climate across tropical Africa, the most serious effects of which are usually felt at the drier margins of agricultural zones or in the regions occupied primarily by pastoral groups. Temperatures throughout Nigeria are more often than not high; diurnal variations are more pronounced than seasonal ones. The Highest temperatures occur during the dry season. Although average temperatures vary little from coastal to inland areas, inland areas, except the North East which has greater extremes. In the North East, temperature reaches its highest peak before rains start and drop to its lowest level during an intrusion of cool air from the North (December to February) (National Bureau of Statistics, 2012).

1.7.3 Vegetation

The vegetation types are accepted in the country based on the climatic conditions. The mangrove and fresh water swamps, the rain forest, the Guinea Savannah, the Sudan Savannah and the Sahel citing South North. Betwixt the rain forest and the Guinea Savannah is a modified vegetation transition consisting of light deciduous forest and derived Savannah. The Southern forest that is both the swamps and the rain forest constitutes the country's main source of wood. The derived Savannah zone, about 250 km wide, was once the Northern part of the forest zone, but transformed by human activities (farming, logging, grazing, hunting, urbanization, road construction) into deciduous trees and grasses. Most of the remaining part of the country is the Sudan

Savannah accounting for more than 25 % of the surface area, and expanding at the expense of the Guinea Savannah. At the North Eastern and North Western corners of the country is the Sahel which accounts for more than 5-10 % of the countries surface's area. This ecological zone described as the Nigerian dry-land by many researchers, contains most of the range-land of the country. Even so, the expansion of cultivation and extreme climatic variations combine together to reduce the grazing areas, to degrade the zone, including changes in plant species (Federal Ministry of Environment of Nigeria, 2009).

CHAPTER TWO

2.0 LITERATURE REVIEW

This section reviews some concepts related to the work such as climate change (CC) and global warming, climate extremes and their indices, Heat Waves (HWs) and regional climate models. These concepts are key concepts to the understanding of the study. Some relevant literature that encompasses the different occurrence and aspects of Heat Waves were also reviewed.

2.1 Conceptual Framework

CC has always been a complex and perplexing topic. Indeed, people still consider it as intangible and irrelevant, but with the number of species and habitats that are walloped it is becoming ever more essential to engage with it (Cornelius, 2016). HWs can also be confusing because of the different definitions and methods to determine the aspects and occurrence in the different part of the world.

2.1.1 Climate change and global warming

The climate can be described as the state of the climate system. As a general definition, climate is the average weather, a statistical description of the weather in terms of variability and the mean of relevant measures over periods of several decades, typically three decades (Intergovernmental Panel on Climate Change (IPCC), 1995). The quantities are frequently surface variables such as temperature, precipitation, and wind.

CC touch on any significant change in the measurement of climate variables such as temperature or precipitation, for an extended period (decades or longer). CC may be the result of natural factors and processes or may be the result of human activities. Global warming then is a term often used similarly with the climate change but there is a slight difference. Global warming refers to the general average increase in the temperature of the atmosphere at the surface of the Earth, it is just an aspect of the global climate change (U.S. Environmental Protection Agency (EPA), 2014). The term global warming is often taken as the situation where there is a global increase in temperature due to the increases in the concentration of greenhouse gases in the atmosphere. CC is the global or regional scale alteration to long-term weather behaviour and global warming is the long-term trend of uprising average temperatures. The Earth's dynamical climate has been ever-changing throughout the chronicle (EPA, 2014).

CC has been identified as a motor of human and environmental critical situation of the 21st century. A well developed knowledge in CC and/or global warming is one of the prima challenges African populations are confronted to nowadays. Furthermore, it has been debated that CC provokes conflicts and it hence becomes adjuratory to achieve a deep understanding of the phenomenon in Africa (Tadesse, 2010). In Nations and Institutions in the world, political and academic attention is now being dedicated to the global warming and CC issue.

A scientific and political accord has been established that CC poses an appreciable threat to Africa, its ecosystems and species. Unless action is undertaken, catastrophic consequences will occur including rising sea-levels, droughts and HWs, and the loss of up to 1/3 of the world's plant and animal species (Tadesse, 2010). Many reports and public statements have also intimated that CC in Africa is a security threat. It poses threats to food and water security.

2.1.2 Climate extremes and climate extreme indices

More climate data have become available recently to allow climate scientists to analyse changes and fluctuations related to climate extreme weather (CEW) and climate events (CE) (Krause *et al.*, 1999). CEW/CE is the occurrence of a numerical quantity of weather or climate variable above/below a threshold value near the upper/lower ends of the range of observed values of the variable. In other words, CEW/CE are collectively considered as climate extremes (IPCC, 2012). Changes in climate extremes have been observed since 1950 and some of them were highly related to human activities, including a lessening in cold temperature extremes and a gain in warm temperature extremes and this in many regions (IPCC, 2014).

From droughts to flooding rains and damaging frosts to HWs, it is obvious that climate extremes are very important and must be considered in every society (Alexander, 2016). CEW/CE have a highly devastating impacts on human societies and ecosystems, and this admit of human lives losses, economic and non-economic impairment and ecological responses (IPCC, 2012; Sippel and Otto, 2014). The climate has warmed and the extremely cold days have reduced in frequency directing to a reduction in frost and freeze frequency, even if this unspecific tendency can be temporally turned with the time. The reduction in the number of coldness, freezing and hoarfrosts is magnified by the fact that the daily minimum temperature is rising faster than the daily maximum temperature. There has also been an inclination toward the increase in the frequency of super warm days, but this trend is anticipated to significantly increase (Krause *et al.*, 1999).

Requirement for three areas of extremes were considered. A first group working on storms considered the cyclones in the tropics and out of tropics, thunderstorms and their joint winds and effects other than on temperatures and precipitation to be in their purview. The second group focused on precipitation. On an assortment of spatio-temporal scales, heavy precipitation cause important damage and deaths and food damage each year. Yet, mechanisms to supervise, interpret, and predict precipitation extremes are greatly deficient because of the deficiency of high-quality information/data and the absence of a combined global effort to do reproducible analyses with the available data. There is also a deficiency of relatively simplex, undifferentiated indices and indicators of precipitation in many areas in the world that can be well used to respond to basic interrogations such as the IPCC question on whether climate that is getting more extreme - these answers can't be provided if each country or area has its own definition. The group determined the indices to be calculated from daily data and the ones to be calculated from hourly data (Krause *et al.*, 1999). The emphasis of the third group working on temperature extremes, is on indicators of important meteorological extremes looking at natural and anthropogenic CC, their detection and social consequences to these. An important property of climate indicators that should be considered is that, indices should be clearly specified and some other is that they should yield warning of tendency liable to have societal impact if they were to prevail.

Different studies sought after characteristics of indices for monitoring CE; according to Krause *et al.* (1999) summary, CE indices should include:

(i) A great signal-to-noise quantitative relation for the detection of a trend or a change from one period to another. Signal is the size of the change being evaluated; noise is the real physical interference in the atmospheric system and not to non-physical measurement error.

(ii) The relevancy of the index to at least an economic activity and other facet of human society and ecological systems.

(iii) Sensitiveness to human/natural-induced fluctuations in climate.

(iv) Possibility to define them with clarity and meaningful over continental to global scale, even though not necessarily everywhere.

(v) Should be computable from acquirable observational and model data.

Temperature indices need significant work and testing to determine for instance, the percentage of missing data to be tolerated or the index sensitivity to different ship-ways of ciphering probability distributions. Issues related to data homogeneity require to be addressed (Zhang *et al.*, 2005). Some basic indices can be computed with temperature as the day-to-day percentiles of maximal, minimal and mean temperature, Diurnal Temperature Range (DTR), inter-period temperature differences, frost/freeze indices (severity, duration) and HW Duration Index (HWDI) and Cold Wave Duration Index (CWDI), stress indices (heat stress and wind chill indices). Some key temperature indices exist also such as Seasonal and annual mean extremes, Diurnal temperature range and Frost severity index (Krause *et al.*, 1999).

Extreme weather incidents are projected to increase as with climate change. Many countries in the world will experience an increase in the number of HWs every year and a liable decrease of terrible cold occurrence. Rainfall events are anticipated to reduce in frequency but the intensity will increase in many areas, droughts are going to be more frequent and severe in places where the mean precipitation is planned to decrease

(University of Winsconsin-Stevens Point (UWSP), 2016). Under CC, agricultural land will be lost because of short growing seasons and lead to lower yields. In Nigeria, wetter than usual conditions were experient in Bauchi, Kaduna, Katsina and Nguru in the North and Ogoja, Ikom, Uyo, Calabar, Benin and Ikeja in the South, causing floods in some areas. Drier than normal circumstances were experient in and around Shaki, Iseyin, Abeokuta, Oshogbo, Yelwa, Gusau, Bida, Minna, Abuja, Ibi and Yola (World Meteorological Organisation (WMO), 2015). HWs affected Sokoto, Kano, and Minna in 1987, Maiduguri in 1983 and Lokoja in 2005 and 1987 (Balogun *et al.*, 2016).

2.1.3 Heat Waves (HWs) and heat related stress

The classification and distribution of the climate of regions around the world, makes some places hotter than others. Both heat and humidity are combined to have a HW, only high temperatures may not be a threat. HWs are difficult to picture, opposite to tornadoes, hurricanes and floods that can easily be captured by destructions and damages that result from them. HWs therefore have a tendency of not having the same visible impact as the cited catastrophes. So far, HWs killed many people in the United States (U.S) compared to all the combined other affiliated atmospheric condition disasters.

HWs come to happen when high pressure rise upward in the higher atmosphere above the earth, from 3,000 to 7,600 meters, gain strength and stays over an area for days and sometimes weeks in the same place. This physical process is communal in summer (in the two Hemispheres) as the jet stream motion with the sun (National Oceanic and Atmospheric Administration (NOAA), 2015). HW studies gain attention recently (since 2000) because of: the ambiguity in the clarity of outline and how it is depicted; the outcomes on humans, animals, plants and the basic structures or features of a system; the underlying reasons; the future postulated sequences of possible events for increased frequency and impact. With opposition to hurricanes, tornadoes or other severe storms, the consciousness of heat as a related atmospheric risk has been greatly under-accredited. Still, HWs are major cause of climate colligate deaths that have wide geographic wallops. During the 2003 summer for instance, HW that affected the West of Europe, peculiarly France and Spain, arrogated more than 35,000 lives (Souch and Grimmond, 2004). The absence of a consistent definition of HWs in the published literature makes it difficult to analyse the frequency, the severity, the duration and its areal extent (Robinson, 2001). Different indices are calculated in different studies due to the different ability of living beings to bear heat. HWs are defined as a period of abnormally hot weather residing permanently for several days according to the Australian Government Bureau of Meteorology (2017).

Basically HWs are defined as a relatively long period of outstandingly high atmosphere-colligated heat stress, that causes ephemeral changes in populations modus vivendi and may have harmful health upshot for them (Robinson, 2001). It is also a period of successive days where the atmospheric circumstances are extremely higher than desirable temperature (Perkins, *et al.*, 2012). HW is interpreted as a period of atypical and dis-comfortably hot atmospheric conditions with high air humidity. Typically, a HW lasts three or more days (Matzarakis and Nastos, 2006). Several definitions could apply to HWs that consider the duration and/or intensity (Robinson, 2001; Meze-Hausken, 2008; Perkins and Alexander, 2012; Smith *et al.*, 2013). Moreover, apprehending heat exposure is much more convoluted than a maximum temperature taken exclusively, this include the two parameters that are the temperature and the humidity; for example, Sparks *et al.* (2002) shows that humidity have a combined effect, where heat stress became stronger with high dew points in Chicago in 1995.

Watts and Kalkstein (2004) developed the heat stress index, an index that measures the nature of daily relative stress for locations and found on departures from the climatology. It used Apparent Temperature (AP) and other derived meteorological variables that are: the cloud cover, the cooling degree days and the back-to-back days of extreme heat). Frich *et al.* (2002) describes HW Duration Index (HWDI) that is the maximum period of 5 or more successive days with maximum temperature greater than 5 °C above the daily normal (1961-1990). It has been created to detect changes in temperature extremes worldwide.

Though this is the first developed index to detect impact of HW, the HWDI has limited value in hot areas with low to very low day variability. For instance, the index cannot be applied in Kuwait, where excess in temperature of 40 °C is frequent (Souch and Grimmond, 2004). Nevertheless, limits were found to the definitions and non robust when doing comparison of the severity of HWs across regions and time. The HW Duration Index (HWDI) defined by Frich *et al.* (2002), one of the first suggested indices to detect HWs' impact, was found to be statistically non robust. Frich *et al.* (2002) used a defined threshold of 5 °C above the norm of the area to calculate the index. This threshold cannot be applied everywhere, because it is too high in many regions where the variation of temperature is not as high, like the tropics, where the daily temperature fluctuation is low (Russo *et al.*, 2014).

In order to solve the issue, the Expert Team on Climate Change Detection and Indices (ETCCDI) added another index, the Warm Spell Duration Index (WSDI) which is computed on a percentile based threshold. In the progress of studies, the joint Commission for Climatology of the World Meteorological Organization's (WMO)/World Climate Research Programme/Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (CCl/WCRP/JCOMM) ETCCDI of which the activities started with a workshop in Bracknell in 1998 has an official document to address the need for the objective measurement and characterization of climate variability and change. The 27 indices that the ETCCDI agreed on were incorporated in a software project named CLIMDEX project. The goal of the project was to ameliorate on the observed indices availability and accessibility, traceability in near real time. The ETCCDI is linked to the Expert Team on Sector-specific Climate Indices (ET-SCI) (ex ET-CRSCI). Activities are conducted to develop tools to generate sector specific indices and promote the use of these indices in different sectors. The Expert Team (ET) work with sector-based agencies and experts to develop 34 indices and a software package called ClimPACT, which is largely based on RClimDex.

Heat Stress is conditions that have the potential to cause physical harm to living things. It may occur at less adverse conditions than those meeting HW criteria. Several methods are used to define heat stress: the univariate, and multivariate indices; and air mass typologies. Any heat stress index can be used as an absolute or relative measure of heat stress. The aim of heat stress indices is to be able to predict with accuracy HW weather situations that may lead to adverse effects in various sectors. While relative and multivariate approaches are desirous for studying human and livestock health, absolute and univariate approaches may be sufficient for studies in other sectors. For example, when looking at the effects of heat on tire blow-outs or on infrastructure such as roads, power lines, and water supply systems, absolute criteria, such as maximum temperature and number of days above some preselected temperature, may be sufficient for prediction (Smoyer-Tomic *et al.*, 2003). Heat stress conditions usually occur with dry spells or drought (Huth *et al.*, 2000; Jiang and Huang, 2000). Heat stress on crops is relative to the tolerance ranges of each plant. In cereal crops, high temperatures during grain filling can decrease the yields (Singletaryab *et al.*, 1994).

For a wide variety of plant species, heat stress initially is more damaging than simple dry spells however, over a longer time, water deficits is most damaging to plants (Jiang and Huang, 2000). Plants can adapt to environmental stress by reducing the number of stomata on leaf surfaces to reduce evapo-transpiration losses and by extending root systems down into the subsurface. All the species don't have the same adaptation capacity to heat stress. In general, plants exposed to temperatures greater than 40 °C experience wilting. If exposure is prolonged, death may result. Furthermore, soil is adversely affected by extreme heat through warming and drying. Root damage, which limits nutrient uptake, may occur in warm soils.

2.1.4 Regional climate models

Observations, theoretical studies, and modelling have been of great importance to improve the understanding of the climate system. They are employed to building and improving computing machines models that reproduce the climate system and engage in predictions/projections about the future behaviour based on statistical and mathematical models. The models help to a better knowledge of the existent relations between the atmosphere-ocean-earth system and climate conditions (UWSP, 2016). A limitation of Global Climate Models (GCMs) is the coarse resolution. A GCM is unable to represent small-scale effects that are important in the climate of a region. The climate can vary dramatically over short distances, especially in the context of precipitation and wind speeds.

Regional Climate Models (RCMs) provide solution to that problem by increasing the resolution of the GCM in a small and well defined area of interest. For example CORDEX (COordinated Regional climate Downscaling EXperiment) is a multi-region, multi-emission scenario, ensemble of RCMs & SDs (statistical downscaling) downscaling an ensemble of GCMs for Regional Climate studies to support impact assessment and adaptation planning (Dahné, 2015).

The results of a projection or better, a prediction from a climate model depend on the scenario used. A scenario is a logical, internally ordered, reliable and plausible description of a possible forthcoming condition of the world. Each scenario is an alternative representation of the future (IPCC, 2013). A scenario is often a simplified storyline of how the future may look like, based on strongly logical set of assumptions about driving forces and key relationships. There are different scenarios but the Representative Concentration Pathways (RCPs) are more typical among the latest.

This work employs for the projection, RCP4.5 and RCP8.5 under Weather Research and Forecasting (WRF) model, a mesoscale numerical weather prediction system performed for both atmospheric research and operational forecasting necessities. WRF model was developed by the National Centre for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration NOAA/NCEP and the Forecast Systems Laboratory (FSL)), the Air Force Weather Agency (AFWA), the Naval Research Laboratory (NRL), the University of Oklahoma (OU), and the Federal Aviation Administration (FAA).

2.2 Review of other Related Studies

In recent years, the warming days have increased and HWs along in their duration and frequency. The changes pattern is remarkable in China. In order to study the changes in hot days (HD) and HWs in China from 1961-2007 Ding *et al.* (2010) defined two temperature aspects for comparison: a HD when the temperature surpass the 90th percentile of the daily temperature norm, and a HW is when the HD last for 3-5 days. The research was to study the spatio-temporal variation of heat waves over china mainland. The homogenized historical data were collected from 1951-2007 across the country. Daily rainfall observations were also collected from the same stations. The least square method is applied with F-test to determine the significance of the regression equation for simulating time series. As result of spatial patterns of hot weather events, HDs and HWs increased significantly in North Western and South Eastern China. The study didn't mention the reasons of the changes in the climate extremes.

Similarly, Gershunov *et al.* (2013) worked on California HWs in the present and future, using daily maximum and minimum temperature (TMAX and TMIN) interpolated onto a regular 12x12 km grid. He defined a HW index by the maximum and minimum temperature and limited only to that. He reported that the four GCMs considered, projected HWs to strengthen the intensity with CC than the past historical characteristic. A trend of HWs, and a progressively enhanced magnitude through the twenty-first century is projected along the coast, the most highly populated and least heat-adapted of all California sub-regions. This trend is already observed over coastal Northern California.

Perkins and Alexander (2012) conducted research on increasing frequency, intensity and duration of observed global HWs and warm spells. He laid emphasis on the fact that HWs needs to be measured because of the future projections in a century. In the course of the work, daily TMIN and TMAX was collected with vapour pressure and rainfall at 0.5 °x0.5 ° grid resolution. A composite technique combining experiential interpolation and fitting function to construct daily gridded observation was applied. All the analysis were carried out for 1951-2008 and 1971-2008 on an individual basis, to examine if various results could come from the different time periods. The indices have been grouped into aspects that represent characteristics of a HW and definition of how the HW is obtained. The findings confirmed the definition of HW as an event of 3 consecutive days. And also the importance of considering multiple HW aspects to understand explicitly the extent of HW behaviour in a given region was shown.

Russo *et al.* (2014), studying the same topic and the appropriate index to define HWs, used a newly developed index to determine magnitude of extreme HWs in existing climate and projected in a heating world. The aim of the study was to quantify the 2010 Russian HWs. Many indices have been developed to quantify the phenomenon and predict its characteristics in the future. Indices such as the HW Duration Index (HWDI) are not robust enough. The ETCCDI developed the Warm Spell Duration Index (WSDI) employing the percentile threshold that was also not robust enough. The HWMI is then developed on a ≥ 3 consecutive days period of the 90^{th} percentiles of maximum temperature as threshold. The HWMI was tested against the other indices and have been found robust enough. The projection has been done with ERA-Interim data (ERA-I) and NCEP-DOE-Reanalysis-2 and the multi-model ensemble from the CIMP5 with distinctly separated scenarios (RCP2.6, RCP4.5 and RCP8.5). The outcomes of HWMI were classified according to the following new developed scale in Table 2.1.

Table 2.1 HWMI Classification

Classification	Heat Wave Magnitude Index (HWMI)
Normal	$1 \leq HWMI < 2$
Moderate	$2 \leq HWMI < 3$
Severe	$3 \leq HWMI < 4$
Extreme	$4 \leq HWMI < 8$
Very extreme	$8 \leq HWMI < 16$
Super extreme	$16 \leq HWMI < 32$
Ultra extreme	$HWMI \geq 32$

Source: Adapted from Ceccherini *et al.* 2016b

The HWMI showed that the extreme Russian HW in 2010 was exceptional under the different scenarios. The percentage of the affected global area increased and will continue increasing in the coming years.

Ceccherini *et al.* (2016b) conducted also a study on magnitude and oftenness of heat and cold waves in late decennary taking as example the South America and using the HWMI**.** This study was done in order to describe the increasing regime of HWs and cold waves throughout the South America over late years (1980-2014). The Global Surface Summary of the Day (GSOD) meteorological data was used. The annual magnitudes of HWs and cold waves were calculated using maximum and minimum temperature. The HWMI was computed along with the Cold Wave Magnitude Index (CWMI) using daily TMIN and TMAX. A trend analysis was carried with the Mann-Kendall test to observe significant tendencies in TMIN and TMAX time series. The results showed an increase in the intensity of HWs, as an ongoing phenomenon.

According to the results, Cold waves contrarily did not change significantly over the time, and the annual temperature range trend is positive out of the tropics and negative in the tropics.

In Africa, many researchers have asserted that the continent is greatly exposed to CC and pointed out the need to assess and know the different variabilities in the changing of climate, spatially and temporally, in different countries and at a regional level. In addressing this challenge, Ceccherini *et al.* (2016a) conducted an experiment using GSOD data coupled with ERA-INTERIM reanalysis data because of lack of data in some part of the continent. The data has been assimilated and produced a single global and uniform data. The final input data after application of the HW Magnitude Index daily (HWMId) were maximum ($HWMId_{tx}$) and minimum ($HWMId_{tn}$) daily temperature on annual basis from 1981-2015. It resulted that, the temperature intensity was increasing with the spatial distribution of HWs. From 1996 positive trend in HWs could be observed with a peak during the period of 2011-2015; but for $HWMId_{tn} \geq 3$, the peak is during 2006-2010. HW frequency increased after 1997, with a mean frequency increased 2 or 3 times. Furthermore, the correlation between maximum and minimum temperature was high but their HWMId results differ significantly the minimum from the maximum. Also, the results showed an increase of $HWMId_{tx}$ during the last 20 years, with Northern, central, East Africa and Madagascar. GSOD observations show infrequent coverage of HWs across Africa. This is in contrast to reanalysis dataset that displays homogeneous coverage. Although, the HWMId is applied, missing data are limiting this work. That aside, prediction with the collected data (47 years) is possible to increase the awareness and the prevention of HWs impacts in the affected societies.

Russo *et al.* (2016) used the Heat Wave Magnitude Index daily (HWMId) (early developed (Russo *et al.*, 2014) and later on improved (Russo *et al.*, 2015) for robustness) to determine when uncommon HWs will become ordinary in this warming Africa. The index was applied on daily temperature reanalysis data to quantify the spatial extent, intensity and frequency of HWs in Africa. The HWMId was calculated on ERA-INTERIM (0.7 °) reanalysis data interpolated on CORDEX-Africa (0.44 °) model outputs for the period 1979-2100 over the Africa domain using the function "extRemes", an R package. The historical and future projection was done using 13 Regional Climate model (RCM) from CORDEX-Africa for the period 1979-2100. The study showed a good methodology, an overall assessment of HW event on CORDEX future scenarios. And it considers also the year 2040 as the year of breakout for intense and regular heat waves in Africa. However, a regional study always reveals detailed information about HWs patterns and the study of the sectoral impacts assess better the phenomenon and expose vulnerabilities.

This subject is also explored at a regional level in West Africa by Nkrumah *et al.* (2011). The study was to determine the trends in daily extreme precipitation and temperature indices over Ghana from 1980 to 2011, 31 years. Daily surface TMIN and TMAX and precipitation data were collected over a network of 22 stations in Ghana for a period of 1960-2011. But because of missing data, 1980-2011 was kept with 20 stations out of the 22. "Rclimdex" was used for the analysis of the data, after a quality control. Only six precipitation indices and six temperature indices explained better the behaviour of the climate of Ghana and employed for discussion. There is an increasing trend in the rainfall pattern over the country as it was for the temperature. The trends on precipitation extremes where not significant across the country, making it difficult to provide climate information for water resource management. They discussed the fact that change in extreme climatic events have significant impacts to society and pose serious threat to the life, welfare and economy. Climate extreme events are related to important changes in temperature and precipitation extreme. Only few works have been done in the whole Africa and particularly in West Africa because of lack of data.

Works have been done on heat waves and their quantification, but few of the works projected the occurrence of heat waves into the future at a regional scale like in Nigeria. For example, Balogun *et al.* (2016) used a robust index the Excess Heat Factor (EHF) to study the occurrence of HWs in Nigeria but was limited to four stations and did not project the occurrence of HWs.

CHAPTER THREE

3.0 MATERIALS AND METHODS

This chapter explains how the data was collected and the analysis steps in order to investigate the Heat Waves (HWs) characteristics/aspects, and their future occurrence using climate scenarios, Representative Concentration Pathways (RCP4.5 and RCP8.5). Means and ways that were used for the data collection are listed here. R statistic software version 3.4.1 with specific packages that are described here, Climate Data Operators (CDO), NetCDF Operators (NCO), LibreOffice Calc, Gnumeric and Linux Terminal Batch codes were used to prepare and analyse the data.

3.1 Data Collection

Climate extreme Indices have many aspects and are numerous (list of 27 indicators agreed by the Expert Team on Climate Change Detection and Indices (ETCCDI) and 34 core indices from Expert Team on Sector-specific Climate Indices (ET-SCI)). The HW indices show different aspects of HW, so computing and comparing multiple index is necessary, in order to know the different patterns in the considered region. Statistical analysis and comparisons are required for the analysis of data.

3.1.1 Climate observation data (1981-2015)

Observed daily weather data of synoptic stations across Nigeria for a period of thirty five (35) years were acquired from the Nigerian Meteorological Agency (NiMet) archives. The dataset includes minimum and maximum temperatures (TMIN, TMAX respectively) for 17 stations from 1981-2015 on daily bases. The stations were selected according to their locations in the climatic zones and the efficiency of the observations. The data were used to detect minimum and maximum temperature trends in Nigeria.

Table 3.1: List of NiMet Stations

N°	Station	Latitude	Longitude	Elevation (m)
1	Asaba	6.20	6.73	46
2	Benin	6.32	5.60	80
3	Calabar	4.97	8.35	63
4	Eket	4.65	7.94	14
5	Ikeja	6.60	3.35	38
6	Jos	9.93	8.89	1290
7	Kaduna	10.52	7.44	632
8	Lokoja	7.81	6.74	44
9	Maiduguri	11.83	13.15	354
10	Minna	9.60	6.55	260
11	Oshogbo	7.78	4.54	304
12	Sokoto	13.02	5.25	302
13	Uyo	5.04	7.91	38
14	Warri	5.52	5.73	6
15	Yelwa	10.88	4.75	243
16	Yola	9.23	12.47	174
17	Zaria	11.13	7.68	664

Source: Author's compilation, 2017

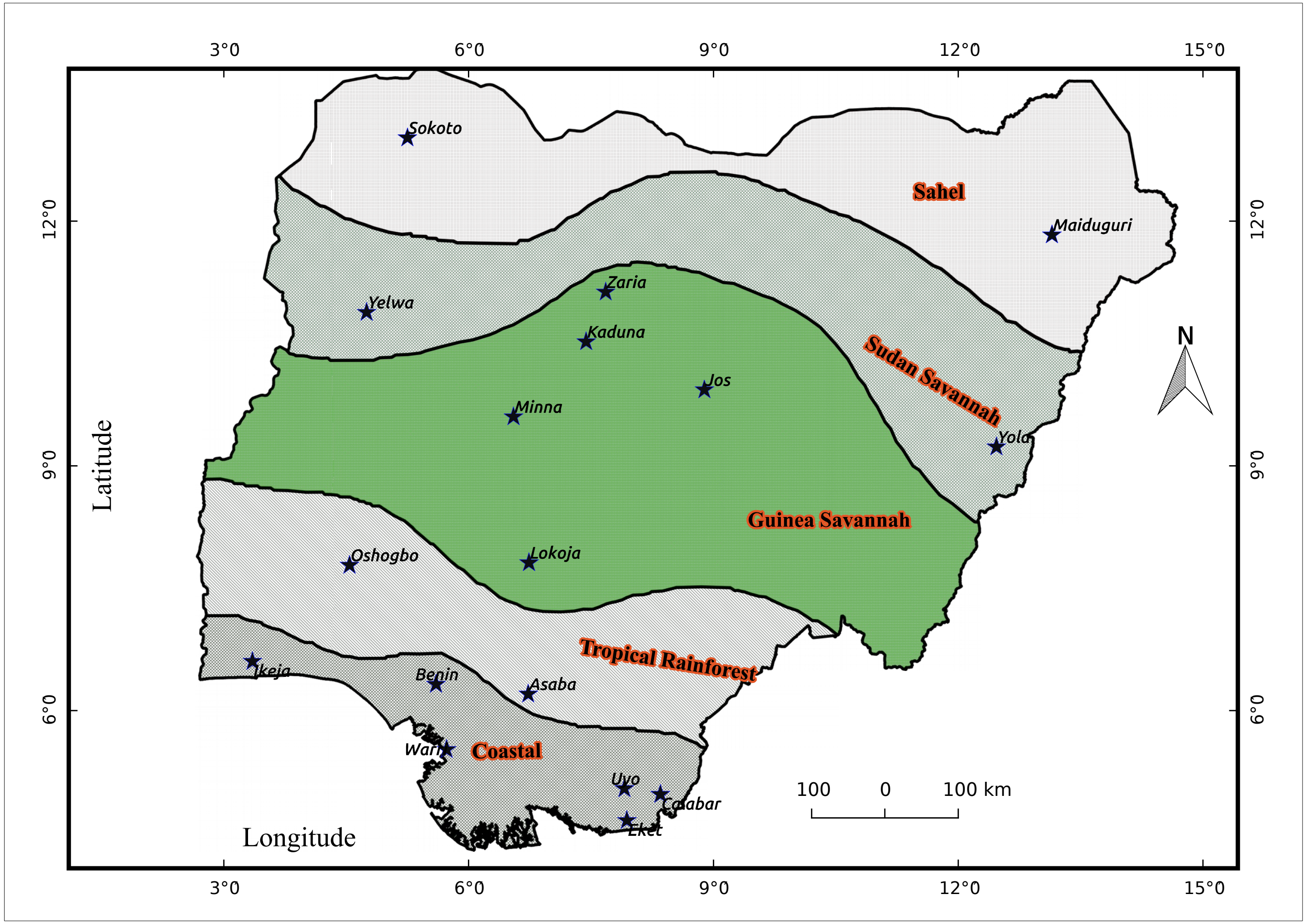

Figure 3.1: Selected Meteorological Stations in each Climatic Zone of Nigeria; Adapted from Akinsanola and Ogunjobi, (2014)

3.1.2 Acquisition of reanalysis and climate scenario data

ERA-INTERIM Reanalysis data was downloaded from the European Centre for Medium-Range Weather Forecasts (ECMWF) public dataset. ERA-Interim a continuously updated global atmospheric reanalysis dataset available from 1979, is an assimilated data system which includes a 4-dimensional variational analysis (4D-Var) running a 12-hour analysis window. ERA-INTERIM dataset was downloaded at 0.1 °/0.1 ° (~ 11 km) from the ECMWF public dataset for the period of thirty seven (37) years, 1980-2016 (first January 1980 to thirty-first December 2016). The data was retrieved using the Linux ecmwfapi integrated into a python code to import "ECMWFDataServer". Specifications have been made to "14/2/3/15" (as geographic lat/long degrees) to subset the area to Nigeria. The time 00 and 12 were requested at steps 3, 6, 9 and 12. The data included daily minimum and maximum temperature at 2 m and total daily precipitation. The downloaded data is a lon/lat gridded data type. A total of 14541 grid-size (131x111) was acquired for analysis.

Simulations from the Weather Research and Forecasting (WRF) at ~ 44 km under CORDEX-AFRICA were requested from WASCAL Graduate Programme centre of the Federal University of Technology Akure (FUTA). The data were collected for a period of eighty-three years (83), from 2018 to 2100, for the prediction of HWs in the study area, Nigeria. The datasets included were Minimum and Maximum Temperature and Precipitation for the two scenarios, RCP4.5 and RCP8.5.

3.2 Data Preparation

The Observation data files were in text format (.WTH). The reanalysis and model outputs were both in NetCDF grid format (.nc). The data needed to be converted and prepared for the processing and analysis.

3.2.1 Data conversion into ET-SCI format (NiMet observations)

The data was converted into ASCII comma separated values (.CSV) files. All the columns were structured as following sequences: YEAR, MONTH, DAY, TMAX, TMIN (the unit of the parameters were in degrees Celsius). The format as described above was a tab delimited format (CSV). The files were converted into time series (TS) format using R statistics.

3.2.2 Model output (WRF) data and NetCDF format

The AFRICA domain that was collected (WRF outputs), were in NetCDF format and they could be used directly to compute the indices. Climate Data Operators (CDO), R statistics and NetCDF Operators (NCO) were used to prepare the data. The AFRICA domain had a total of 17 files of a period of 5 years each. They were merged into unique NetCDF file format with CDO. The created file was next subset to Nigeria geographic coordinate that is the study area, and saved into NetCDF. And finally to unstagger the WRF output, a bilinear remapping was applied on the NetCDF file to "longitude/latitude" grid and interpolated using the Inverse Distance Weighing (IDW method) from quadrilateral curvilinear grids to regular grids of 0.1 °/0.1 ° (~ 11 km) like the ERA-INTERIM files.

For usage in the Climpact2 software, the created files were processed with NCO to change the variable names from "*pr*", "*tasmax*" and "*tasmin*" to "*precip*", "*tmax*" and "*tmin*" respectively. The different files were merged into one NetCDF file of three variables and three dimensions (longitude, latitude and time) without "bounds" attributes in the latitude and longitude variables. Precipitation had to be added for the process to run smoothly and precipitation variable was of units "kg m^{-2} d^{-1}", not "mm/day" even though they are equivalent. The Climpact2 downloaded package code was modified to adapt to the needs of this study.

3.3 Data Analysis

The analysis was carried on the data following the defined objectives in order to address the respective research questions.

3.3.1 Trend analysis and significance testing

A trend is a long-term change (increase or decrease) in a time series (TS). A trend analysis is usually used in climatology to know how the temperature for example, is changing with the time. It is also useful in predicting the future behaviour of parameters (temperature in this study). The climate data was collected over a period of 1981-2015 and was subjected to Mann-Kendall (MK) and Sen's Slope test in order to discover or determine the existence of trends in the TS (Ceccherini *et al.*, 2016b). This method is a well known and used one since it has been initiated by Mann (1945) and Kendall (1975) and then modified by Sneyers (1990). The Mann-Kendall MK test is a simple but robust non parametric test by the approach, it takes into accounts missing measurements, serial correlation and values under a detection extent that is usually confusing in trend detection operation in TS analysis (Deo *et al.*, 2005; Önöz and Bayazit, 2003). The MK test is used to evaluate the trend and the slope in the time series data collected from NiMet. Autocorrelation using R statistics' Autocorrelation function (ACF) and Partial Autocorrelation function (PACF) was tested to detect serial correlations in the time series data. Then the normal Mann-Kendall test would have been carried on the time series data if the data had been non autocorrelated or the Modified Mann-Kendall (MMK) method (Hamed and Rao, 1998; Blain, 2013) would have been used to remove the serial correlation if the autocorrelation test was positive. The magnitude of the slope of the TS was measured using Sen's slope method. The autocorrelation test is given by:

$$\rho(k) = \frac{\frac{1}{n-k}\sum_{t=k+1}^{n}(y_t - \bar{y})(y_{t-k} - \bar{y})}{\sqrt{\frac{1}{n}\sum_{t=1}^{n}(y_t - \bar{y})}\sqrt{\frac{1}{n} - k\sum_{t=k+1}^{n}(y_{t-k} - \bar{y})}} \tag{3.1}$$

where ỹ is the sample mean of the data.

And the Mann-Kendall test statistic is given by:

$$S = \sum_{i=1}^{n-1}\sum_{j=i-1}^{n} Sgn(X_j - X_i) \tag{3.2}$$

where X_i and X_j are the sequential data values, n is the data set record length.

The LOWESS (Locally Weighted Scatter-plot Smoothing) or LOESS (Locally Weighted Smoothing), in regression analysis is used to create a smooth line through the time series in order to visually show trends in the data (Cleveland, 1979). The LOWESS was used for the plots in R statistics.

3.3.2 Computation of different Heat Indices

In order to compute the HW indices, the study area (Nigeria) was divided into climatic zones (Coastal, Tropical Rainforest, Guinea Savannah, Sudan Savannah and the Sahel). This helped to determine the HW behaviour in the five different zones, that have different climate configuration, over time and to compare them.

There are 27 ETCCDI indices, 16 related to temperature and 11 for other indices taken into account such as precipitation extremes. There are other indices developed to evaluate and compare the intensity and severity of HWs, the HWMId have been developed to strengthen or take into consideration an aspect of HWs that was not taken into account by the existing ones. Among the developed indices, a total of 6 were analysed.

TN = daily minimum temperature; TX = daily maximum temperature and PR = daily precipitation are required. Daily mean temperature (TM) is computed from TM = (TX + TN)/2. Diurnal temperature range (DTR) is calculated from DTR = TX – TN.

Table 3.2 list of Computed Indices (Heat Wave and Temperature Related)

N°	Metric	Description	Reference
1	TX90p Amount of hot days	Percentage of days when TX > 90^{th} percentile. Fraction of days with hot day time temperatures. Time scale = Annual	ETCCDI (http://etccdi.pacificclimate.org/list_27_indices.shtml): (Alexander *et al.*, 2006)
2	TN90p Amount of warm nights	Percentage of days when TN > 90^{th} percentile Fraction of days with warm night time temperatures Time scale = Annual	ETCCDI (http://etccdi.pacificclimate.org/list_27_indices.shtml): (Alexander *et al.*, 2006)
3	TXx Max TX	The Warmest daily TX The Hottest day; Time scale = Mon/Ann;	ETCCDI (http://etccdi.pacificclimate.org/list_27_indices.shtml)
4	TNx Max TN	The Warmest daily TN The Hottest night ; Time scale = Mon/Ann	ETCCDI (http://etccdi.pacificclimate.org/list_27_indices.shtml)
5	HWMId Heat-Wave Magnitude Index daily	Period ≥ 3 consecutive days where TX is above the daily threshold for the reference period 1980-2011. The threshold is defined as the 90^{th} percentile of daily maxima, centred on a 31-day window. Therefore, for a given day d, the threshold is the 90^{th} percentile of the set of data	(Russo *et al.*, 2015)
6	EHF Excess Heat Factor	Considers daily Tmax and Tmin: T=(Tmax+Tmin)/2 Includes an acclimatization factor (monthly): EHI(accl.) = (Ti + Ti−1 + Ti−2)/3 − (Ti−3 + ...+ Ti−32)/30 And a significance factor: EHI(sig.) = (Ti + Ti−1 + Ti−2)/3 − T95(clim) EHI(sig.) = (Ti + Ti−1 + Ti−2)/3 − T90(cal) Which are combined: EHF = max[1, EHI(accl.) * EHI(sig.)]	Excess Heat Factor (EHF) developed by the Bureau of Meteorology EHF = Excess Heat * Heat Stress (Perkins and Alexander, 2013)

Source: Author's compilation, 2017

5 aspects of HW are analysed:

(i) The yearly number of HWs (HWN), HW events (>= 3 HW days) that begin in the period of interest in addition to those that start prior to but continue into the period of interest

(ii) The duration of the longest yearly event (HWD), length in days of the longest HW defined by HWN

(iii) The yearly sum of participating HW days, HW Frequency (HWF), number of days contributing to HWs defined by HWN (called HW days)

(iv) The warmest day of the hottest annual event (HWA), the off-peak daily value in the hottest HW and

(v) The average magnitude of all annual HWs (HWM), the mean of the mean HW days of each HW defined by HWN.

For the HW aspects, three definitions are used (TN90, TX90 and Excess Heat Factor (EHF)). A HW is considered here as three or more consecutive days where TN > 90^{th} percentile of TN, TX > 90^{th} percentile of TX and the EHF is positive.

$$EHI(accl.) = [(TM_i TM_{i-1} + TM_{i-2})/3] - [(TM_{i-3} + \cdots + T_{mi-32})/30]$$
$$EHI(sig) = [(TM_i + TM_{i-i} + TM_{i-2})/3] - TM90_i$$

(3.3)

where TM_i stand for the average daily temperature for day i and $TM90_i$ is the 90^{th} percentile of TM over all calendar day i. The EHF is defined from the above two definitions:

$$\begin{cases} M_d(T_d) = \frac{T_d - T_{30y25p}}{T_{30y25p}} & ifT_d > T_{30y25p} \\ 0 \quad ifT_d \leq T_{30y25p} \end{cases}$$

$$EHF = EHI(sig.)x \quad max(1, EHI(accl.)) \tag{3.4}$$

The reference period used was 1980-2010 and for each day a 15 day running window was used as specified by the software. Heat waves were calculated in ClimPACT2 over the extended summer period May to September except for EHF. The thresholds were computed and used: TMAX (Coastal zone = 31 °C, Tropical Rainfall zone = 33 °C with Jos Plateau in the Sudan Savannah, Guinea Savannah = 37 °C, Sudan Savannah = 34 °C and the Sahel = 34 °C); TMIN (Coastal, Tropical Rainfall and Guinea Savannah = 23 °C, Sudan Savannah and Sahel = 18 °C).

The Heat Wave Magnitude Index daily (HWMId) analysis had been carried on the TMIN and TMAX. The index considers the duration of the heat waves on top of the severity of temperature extremes. The data was processed with R Statistics extremes libraries like: "*extRemes*" that is a package (Russo *et al.*, 2015; Ceccherini *et al.*, 2016a) for extreme events with HWMId function. The projected and the observed data were processed into climpact2 package with daily Temperature (TMAX and TMIN) data.

HWMId defines HW as the 90^{th} percentile of daily maxima temperature, centred on a 31 day window (Russo *et al., 2015*) giving:

$$A_d = \coprod_{y=1980}^{2011} \coprod_{i=d-15}^{d+15} T_{y,i}, \tag{3.5}$$

where $\coprod$ is the union of different sets and $T_{y,i}$ is the daily TMAX of day i in the year *y*. The HWMId sums the magnitude of sequential days forming a HW, with daily magnitude obtained as follows:

(3.6)

3.3.3 Model and prediction

Prediction with WRF model output data (from the CORDEX Africa domain) was done using the ERA-Interim data as the validation period data from 1980 to 2011 for the HWMId. The thresholds used for the HW indices defined by ET-SCI were from 1980 to 2016. The selected HWs indices were processed with the model outputs. This was to determine under the realistic and the extremes scenarios RCP4.5 and RCP8.5 respectively, HW number, duration, frequency, amplitude and magnitude in the future (2100) in Nigeria. The Weather Research and Forecast model output data v3.3 developed by the National Centre for Atmospheric Research (NCAR), and other organisations and Universities, was used as model for the prediction. The process was run into three (3) steps according to the procedure established by ET-SCI. The present period was run first (1981-2016), then the thresholds were computed from the same base period. Finally, the predicted indices were computed using the WRF output (2018-2100) and integrating the base period thresholds (1981-2016).

3.3.4 Trend analysis on the HWs characteristics (1981-2100)

A spatio-temporal trend analysis was carried on the results of the computed indices to check for significant trends over the time and space of the HW characteristics (5) studied, and evaluate their slopes evaluated. R statistics was used to compute the trend for each grid cell value of the NetCDF file. The trend was computed using the Annual Aggregated Time series (AAT method) on the data (HWs characteristics). The AAT method computes tendencies and trend changes on yearly aggregated TS (Forkel *et al.*, 2013). The data was already in annual aggregate, so no need for aggregation and no breakpoint was estimated on the annual data. The significance of the trend was calculated by the Mann-Kendall trend test applied on the HW characteristics computed quantities.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

The results of the analysis of the study, in-order to address issues raised by the research questions, were presented in this chapter. The results were discussed at the same time in the same order as enumerated in the objectives.

4.1 Temperature Trend in Nigeria

The temperature trend plotted by applying the Locally Weighted Scatter-plot Smoothing method (LOWESS) using R statistics are shown in the Appendix A. Generally, the stations are showing a very low positive trend except for the maximum temperature of Eket and the minimum temperature of Minna. This trend was verified by applying the Mann-Kendall test to check the significance and the importance of the trend. The Sen's Slope showed very low values confirming the smoothed line of the LOWESS trend in the Appendix A (plots).

Autocorrelation has been done in R statistics using the Autocorrelation Function (ACF) and the Partial Autocorrelation Function (PACF) on the time series data to check for serial correlation or not and the autocorrelation was vary high for all the stations (see Appendix B). This correlation is confirmed by Ljung-Box test statistic (Ljung and Box, 1978) that analyse the null hypothesis (H_0) of independence in the series of data with a p-value ≤ 0.05. The MK test could not directly be tested on the data as it was, without removing the serial correlation. The Modified MK (MMK) was then used to take into consideration the serial correlation (Ljung and Box, 1978; Hamed and Rao, 1998; Hamed, 2008; Blain, 2013). The results of the Modified Mann-Kendall test on the TS are shown in Table 4.1 and Table 4.2. The MMK test, returns the corrected p-values after taking into account the temporal pseudo-replication.

Table 4.1: Trend Analysis Results (Asaba, Benin, Calabar, Eket, Ikeja, Jos, Kaduna, Lokoja, Maiduguri and Minna)

Station		Z	p-value	Zc	Corrected p.value	tau	N/*s	Sen's Slope
Asaba	Tmax	17.0576	3.068897E-65	6.495085	8.298666E-11	0.100195	6.897098	7.741436E-05
	Tmin	2.331348	0.01973502	0.3393205	0.7343683	0.01357087	47.20564	0
Benin	Tmax	5.083922	3.697204E-07	1.606248	0.1082195	0.02987146	10.01781	0
	Tmin	15.3046	7.156348E-53	5.800167	6.624896E-09	0.0894123	6.962195	0
Calabar	Tmax	3.007949	0.002630173	0.9982552	0.3181556	0.01765228	9.079414	0
	Tmin	5.100287	3.391381E-07	0.6821902	0.4951187	0.02957869	55.89569	0
Eket	Tmax	-48.80543	0	-6.20959	5.312308E-10	-0.2862118	61.77466	-0.0002602134
	Tmin	36.41207	2.742497E-290	2.50363	0.01229266	0.2112739	211.5196	0.0001103509
Ikeja	Tmax	9.146695	5.87E-20	2.038035	0.04154645	0.053766	20.14212	0
	Tmin	17.63197	1.399969E-69	6.218379	5.023155E-10	0.1031006	8.039839	0
Jos	Tmax	4.16.623	3.530584E-05	1.824735	0.0680411	0.02432827	5.138188	0
	Tmin	4.18385	2.86613E-05	1.287319	0.1979832	0.02457287	10.56282	0
Kaduna	Tmax	4.300341	1.705354E-05	2.283307	0.02241232	0.02530932	3.547132	0
	Tmin	7.666634	1.765689E-14	4.506746	6.582927E-06	0.04509436	2.893898	0
Lokoja	Tmax	0.8812804	0.3781661	0.3314166	0.7403298	0.005188824	7.07098	0
	Tmin	17.18318	3.549289E-66	7.53524	4.874391E-14	0.1008003	5.200113	5.093725E-05
Maiduguri	Tmax	2.945369	1.418007	0.1561887	0.1561887	0.01734908	4.314423	0
	Tmin	6.141068	8.196848E-10	2.538315	0.01113877	0.03617787	5.853246	0
Minna	Tmax	3.901861	9.545612E-05	2.172549	0.022981427	0.02297381	3.225554	0
	Tmin	1.454795	0.1457261	0.3535624	0.7236669	0.008542814	16.93256	0

Source: Author's computation, 2017

Table 4.2: Trend Analysis Results (Oshogbo, Sokoto, Uyo, Warri, Yelwa, Yola and Zaria)

Station		Z	p-value	Zc	Corrected p-value	tau	N/*s	Sen's Slope
Oshogbo	Tmax	5.250886	1.513692E-07	2.460223	0.01388509	0.03087396	4.555294	0
	Tmin	10.97793	4.879736E-28	1.423555	0.1545753	0.06427912	59.46924	0
Sokoto	Tmax	8.669262	4.349306E-18	6.064098	1.326959E-09	0.05105639	2.043769	3.694809E-05
	Tmin	-1.403808	0.160376	-0.6053804	0.5449263	-0.008266864	5.377231	0
Uyo	Tmax	1.333391	0.1824034	0.198415	0.8427204	0.007830454	45.16128	0
	Tmin	30.14207	1.362763E-199	5.699836	1.19923E-08	0.1751959	27.96542	5.382131E-05
Warri	Tmax	15.7916	3.55425E-56	8.371986	5.665515E-17	0.0927487	3.557914	4.136334E-05
	Tmin	16.1812	6.844621E-59	3.369969	0.0007517652	0.09440397	23.05524	0
Yelwa	Tmax	3.489434	0.0004840444	1.41697	0.1564916	0.02055245	6.064408	0
	Tmin	9.936856	2.877661E-23	1.992032	0.04636752	0.5850022	24.88314	4.944376E-05
Yola	Tmax	0.1483275	0.8820843	0.04956274	0.9604708	0.0008737498	8.956379	0
	Tmin	9.095947	9.376571E-20	2.88898	0.003864933	0.05354771	9.913036	3.008122E-05
Zaria	Tmax	3.36024	0.0007787475	1.215623	0.2241287	0.01977629	7.640873	0
	Tmin	10.9405	7.378836E-28	6.221163	4.934843E-10	0.06432934	3.092656	1.121831E-05

Source: Author's computation, 2017

Table 4.1 and Table 4.2 shows the results of the Modified Mann Kendall test on each of the stations minimum and maximum temperature where,

(i) Z is the original (uncorrected) Mann-Kendall test Z statistic,
(ii) p-value is the original (uncorrected) Mann-Kendall test p-value,
(iii) Zc is the corrected Z statistic,
(iv) Corrected p-value is the calculated p-value considering the autocorrelation
(v) tau is the Mann-Kendall's tau statistic,
(vi) N/n*s is the Value of the correction factor standing for the ratio of the number of samples N divided by the effective sample size (n*s),
(vii) Sen’s slope is the slope/magnitude of the linear trend according to Sen test.

The MMK test appears to be strongly significant before adjustment (p-value in the tables), but the corrected p-value is less significant. The values of MK tau (τ) were statistically low leading to equivalently low statistical trend of the series. The slope of the Theil-Sen (Sen’s Slope) was also significantly close to zero confirming the low magnitude of the trend observed in the plots in Appendix A. The results of the Modified MK test on the different sites revealed a significant but very low positive trend in some stations like Asaba, Sokoto and Warri where the slope of the maximum temperature is very close to 0. The maximum temperature of Eket shows a significant but very low negative trend while the minimum temperature shows a positive trend. These results follow the same statistical trend reported by Oluwatobi and Oluwakemi (2016) in South West of Nigeria where the trend of temperature was positively significant. The low significance and magnitude of the slope of the trends are the facts of daily units used for this analysis. All the sites experienced variations in the minimum and maximum temperature, but the trends were very low even though they were statistically significant. These fluctuations will continue and the trend will increase with the actual conditions where climate change is occurring. The decreasing and increasing tendencies in the minimum and maximum temperature (TMIN and TMAX) was also captured by Akinsanola and Ogunjobi, (2014).

4.2 Temperature Indices

4.2.1 The hottest days and hottest nights (TXx and TNx)

Analysis of the hottest days (TXx) from 1981-2016 showed that the zonal TXx in Nigeria have been varying within 30-45 °C. The pattern was obvious in the Figure 4.1a,b. From 1981 to 1988 the warmest days reached 45 °C in the Sahelian zone of Nigeria. Mainly Borno and Sokoto State had the hottest daily days. The Sudan Savannah and Guinea Savannah had a daily TXx between 35-40 °C, while the Tropical Rainforest and the Coastal zone had the coolest TXx of 30-35 °C. The same pattern was observed for the entire Nigeria except for some years like 1987 and 2010 where the hottest values of the Sahel occurred in the Sudan and Guinea Savannah. From 2010-2016 there were no considerable variation in the pattern of TXx.

The hottest nights (TNx) were similarly located in the Northern part of Nigeria where the temperature in degree Celsius reaches 32 °C the night. The Sahel is hotter especially in Borno and Sokoto States. The Sudan Savannah and Guinea Savannah zone's temperature vary between 24 and 28 °C with a low temperature in the middle where Jos Plateau is located. Around the Plateau of Jos, TNx are maintained between 27 °C and 29 °C except for the Southern part that leads to the Tropical Rainforest.

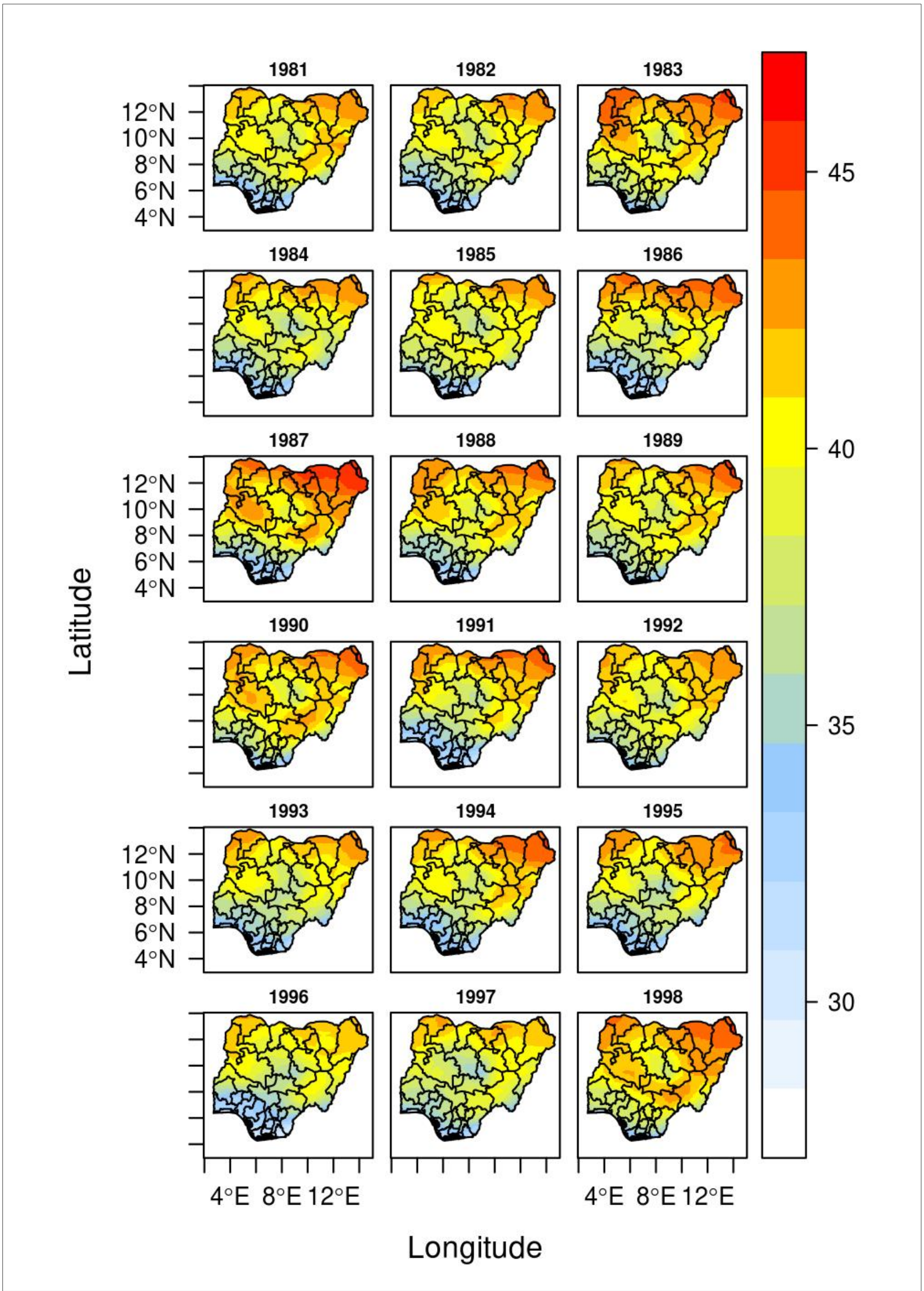

Figure 4.1a Hottest Days in °C (TXx): 1981-1998

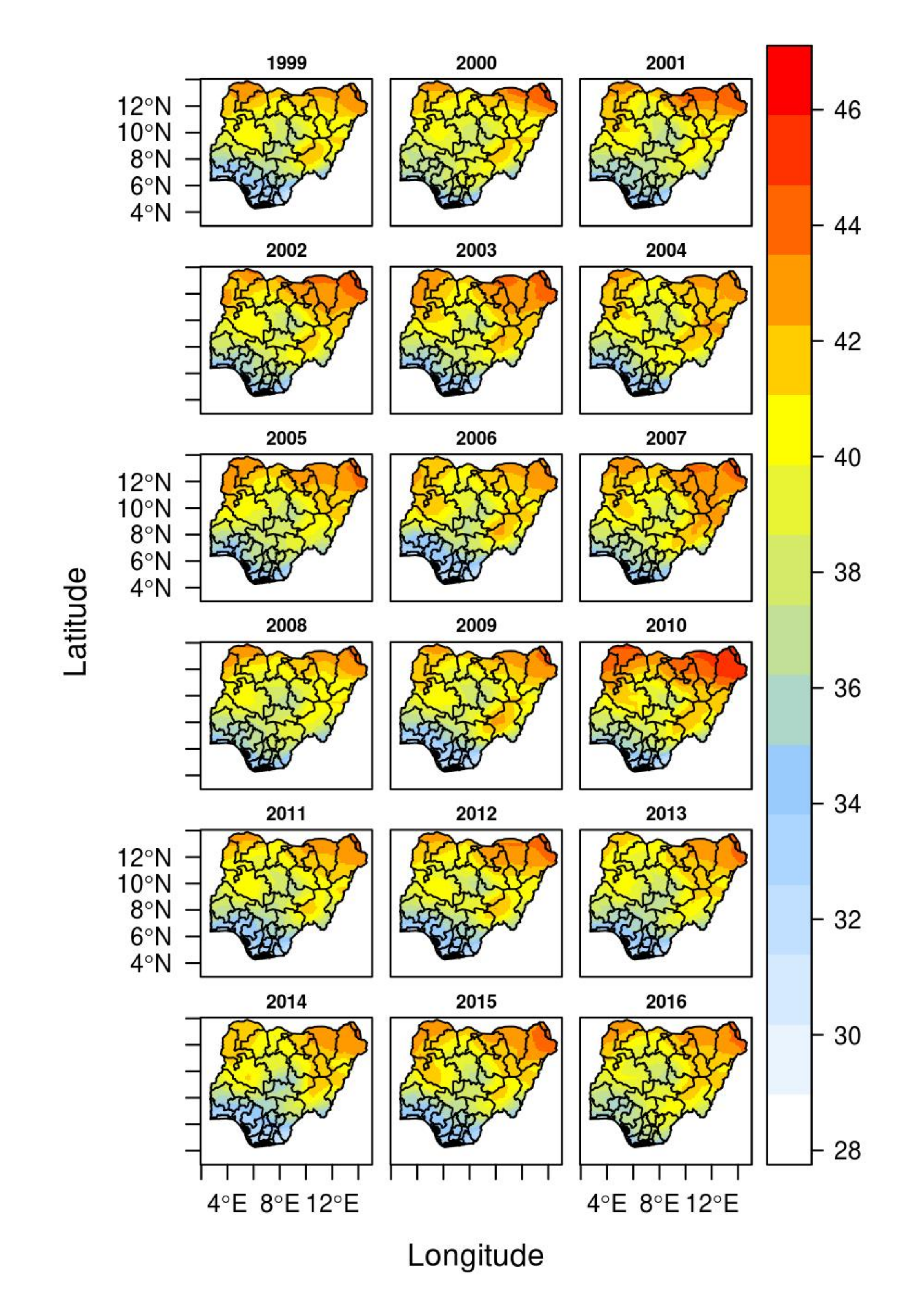

Figure 4.1b Hottest Days in °C (TXx): 1999-2016

The coolest night of TNx were observed in the Coastal, Tropical Rainforest and the Jos Plateau having 22-24 °C in average for the period 1981-2016. The recent years from 2009 experienced hottest TNx showing an increase in the hot night temperatures where the minimum temperature increased from 22 °C to 24 °C as shown in Figure 4.2a,b.

The spatial distribution of TXx and TNx is similar over the years. The Sahel is hotter than the Coastal zone, with the Guinea Savannah and Sudan Savannah in between. The days and nights are hotter in the North of Nigeria than in the South. TXx and TNx decrease with the latitude similarly to the maximum and minimum temperature's pattern. But the temporal pattern showed a slight increase with the year. The results are similar to Revadekar *et al.* (2012) when he observed a spatial variation in the hottest days and nights in India where the climatic conditions are similar with the West Africa. The increase in the minimum temperature explains well the higher spatial variation of the TNx compared to the TXx as observed by New *et al.* (2006).

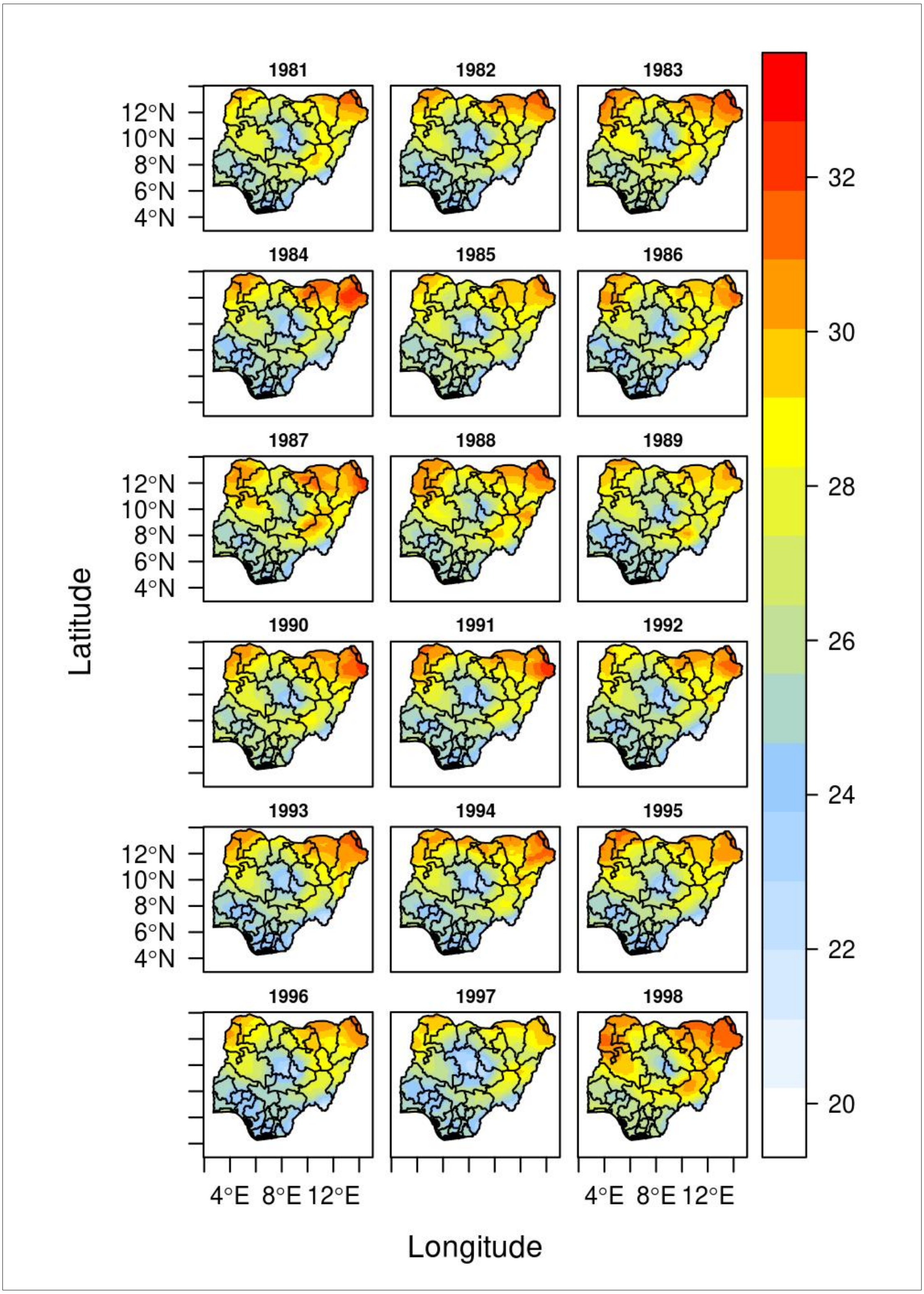

Figure 4.2a Hottest Nights in °C (TNx); 1981-1998

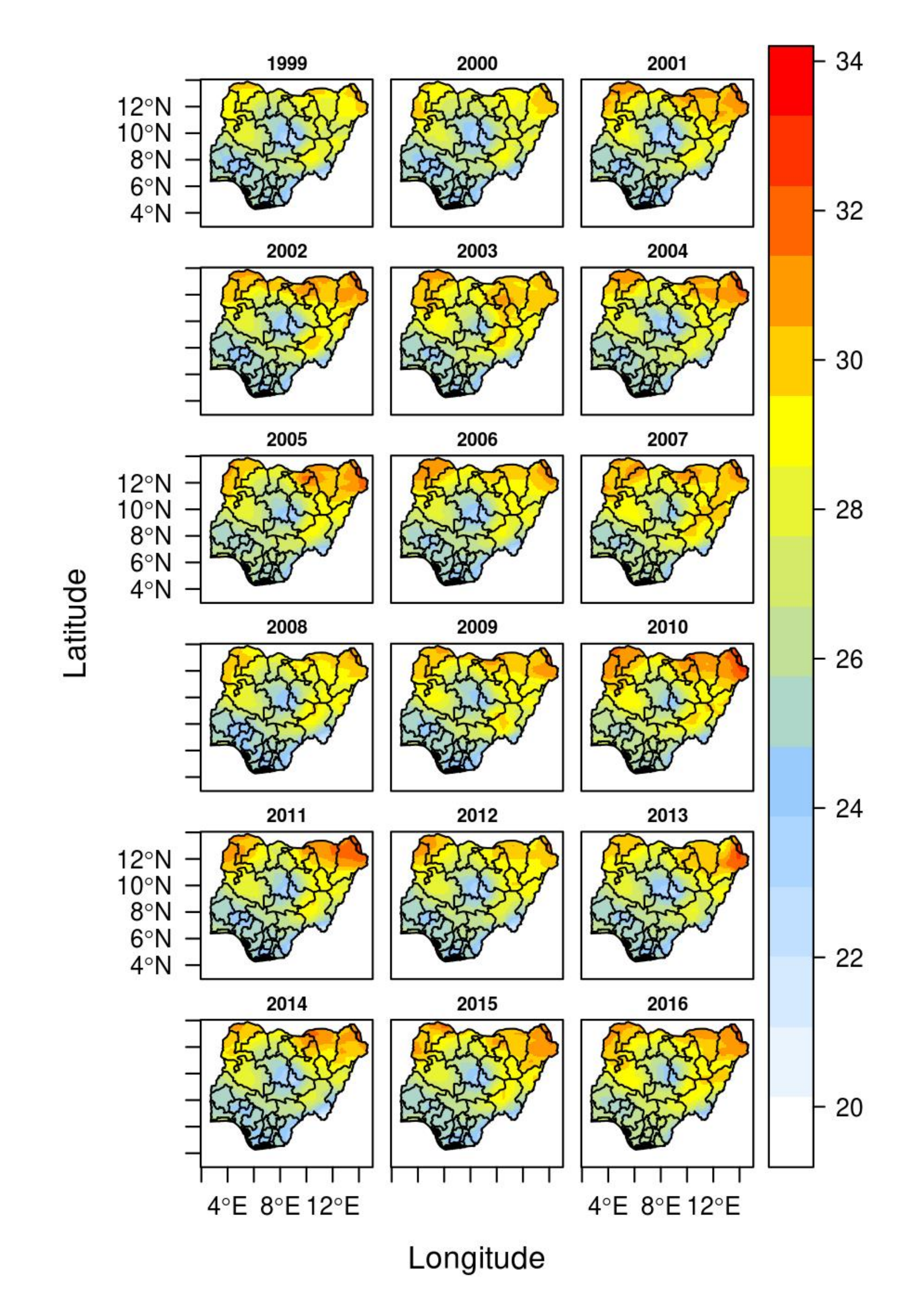

Figure 4.2b Hottest Nights in °C (TNx); 1999-2016

4.2.2 Heat Wave (HW) aspects/characteristics in the present time

4.2.2.1 Heat Wave Number (HWN) for TX90, TN90 and EHF

The HWN for TX90 is the number of HW events (>= 3 HW days) on the 90th percentile of TX (maximum daily temperature). The results in Figure 4.3a,b show that HW events occurred in Nigeria since 1981 and the number vary from no events (0) in some area to 19 events in some other places. In 1983 and 1987 the high HWN was 8 and 10 respectively; and the highest values were located in the North covering Zamfara, Borno, Yobe, Jigawa, Sokoto and Kebbi States. Also the Southern part of Nigeria recorded HW of 3 to 5 events/year especially from 1996 to 2000 covering the Eastern part of the Coastal and Tropical rainforest. The major area were in the South East with Bayelsa, Imo, Anambra, Rivers and Abia. In the year 2000s the HWs covered almost all Nigeria with an increased number of events/year. The year 2007 experienced the highest number of events with 19 events in the Eastern part of the country. The number of events increased in average from 2009 to 2016 with an average of 4 to 8 events a year.

The HWN for TN90 is the number of HW events (>= 3 HW days) on the 90th percentile of TN (minimum daily temperature). In Figure 4.4a,b, the HWN for TN90 followed the same pattern with the HWN for TX90 but the maximum number of events were 17 and 16 respectively in 1987 and 2007 in the South and South East covering all the Coastal and Tropical Rainforest zones and entering into the Guinea Savannah. HW of minimum two events occurred everywhere in Nigeria in 1983, 2005 to 2016, while the year 1992 showed a particularly low HWN (1) in the country. From 2006, the high numbers were found more in the Sudan Savannah and the Sahelian zone. In general, the Sudan and the Sahel had the highest HWN.

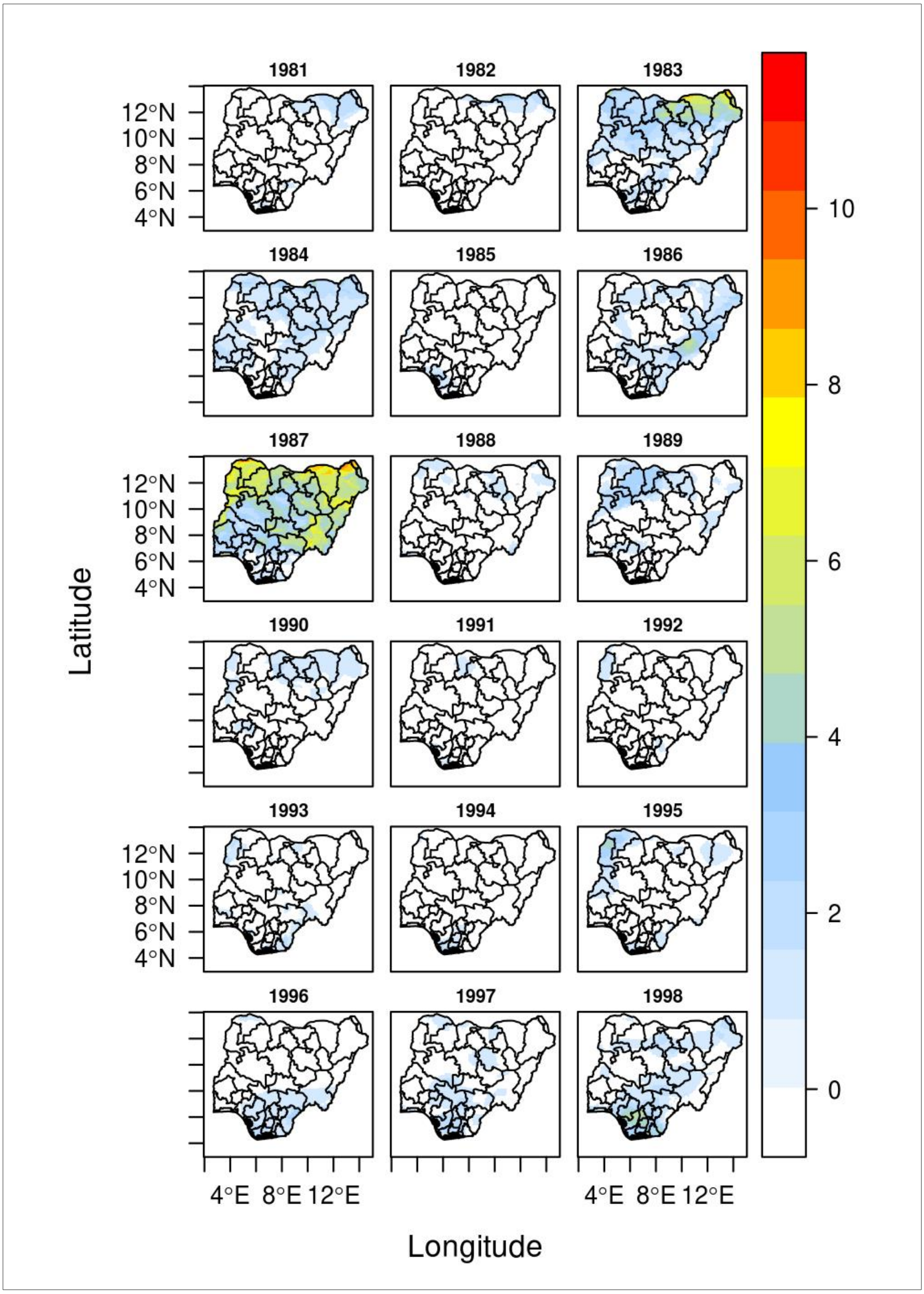

Figure 4.3a Heat Wave Number (HWN) for TX90; 1981-1998

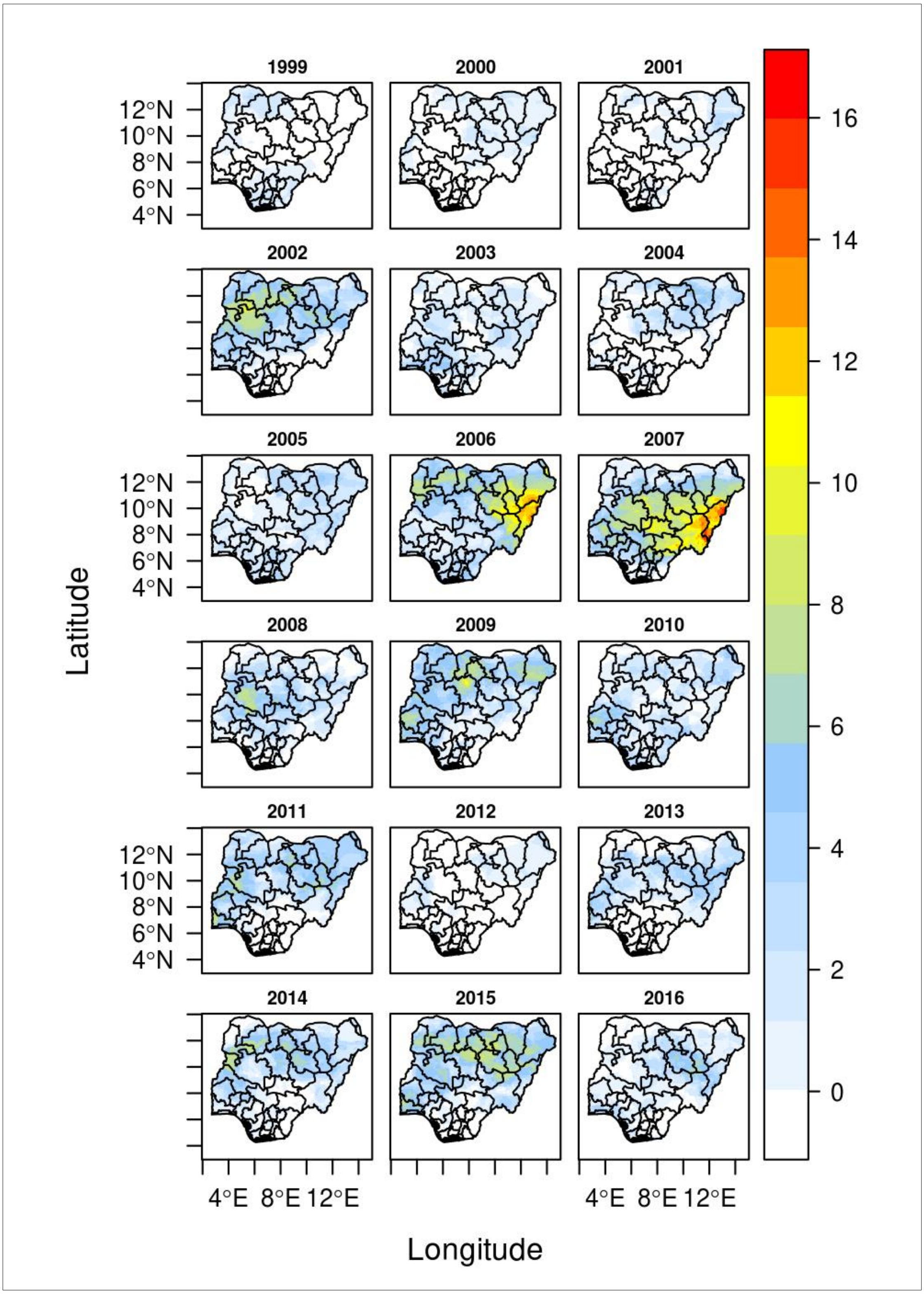

Figure 4.3b Heat Wave Number (HWN) for TX90; 1999-2016

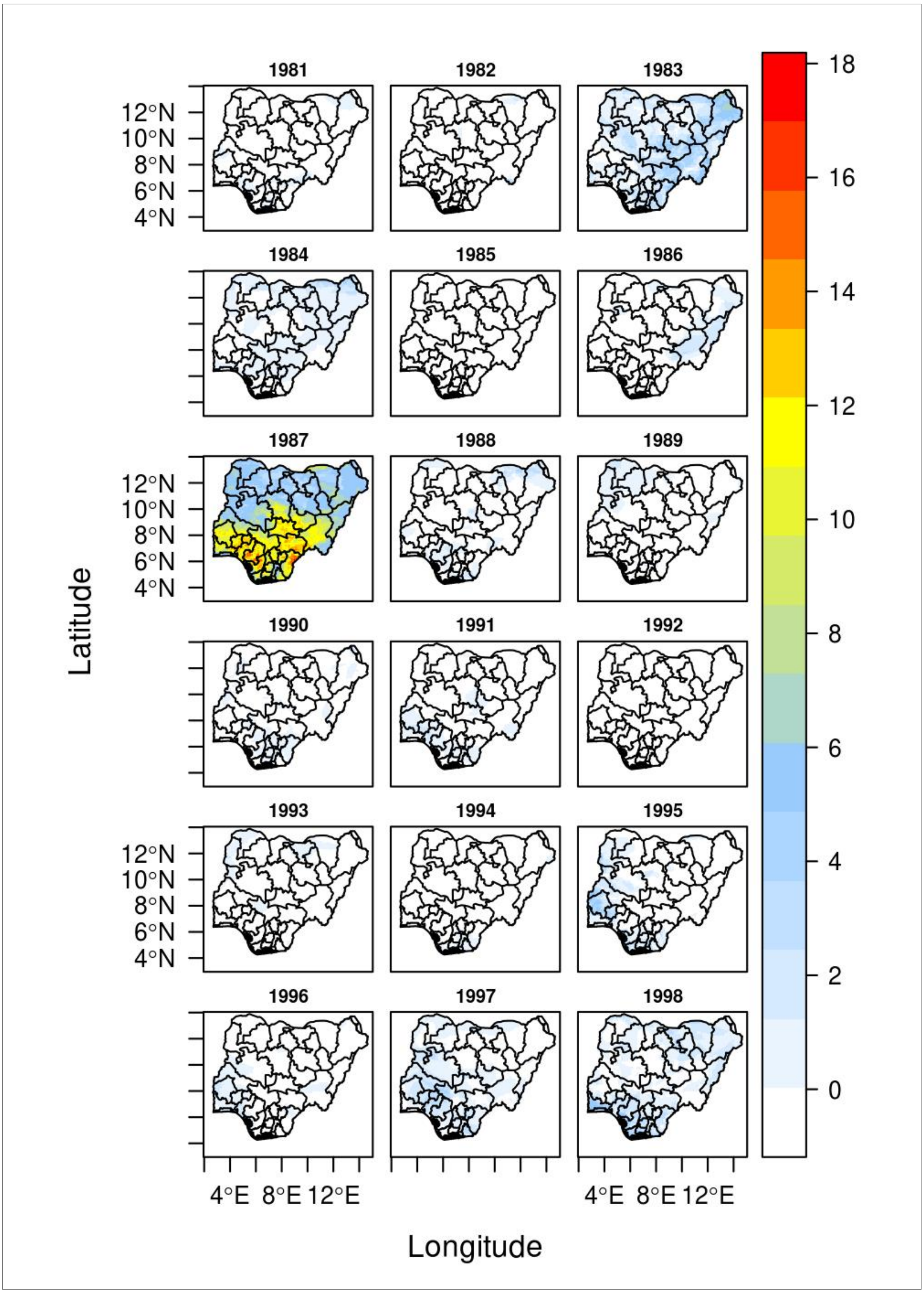

Figure 4.4a Heat Wave Number (HWN) for TN90; 1981-1998

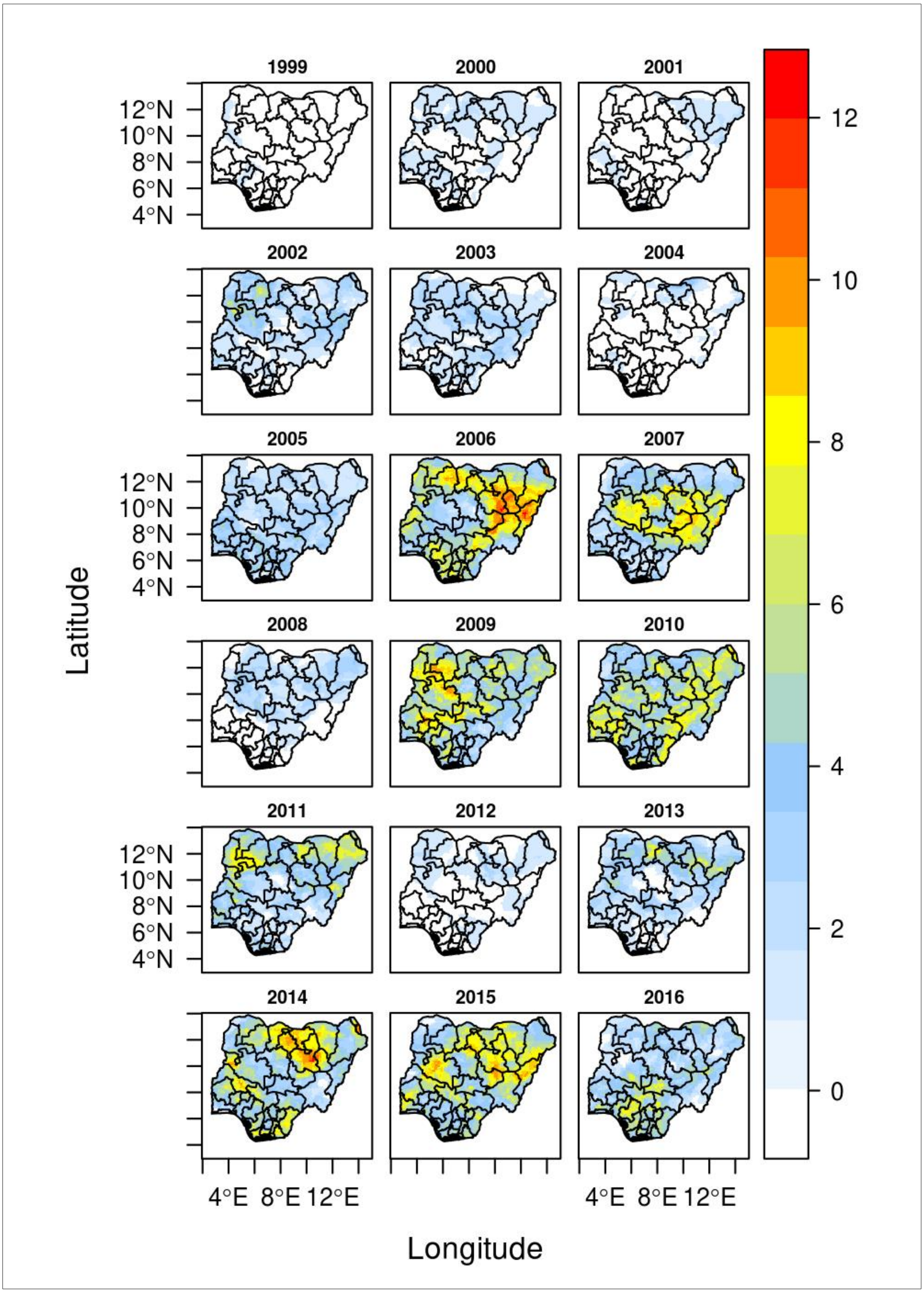

Figure 4.4b Heat Wave Number (HWN) for TN90; 1999-2016

The Excess Heat Factor (EHF) is also a good index used for HW. The EHF is a combination of a couple of excess heat indices (EHI) representing the acclimatisation (EHI(accl.)) to heat and the climatological significance (EHI(sig.)). The HWN using EHF is spatially similar to the previous definitions of HWN (TX90 and TN90). In 1981 the high HWN were located in the Sahel, in Borno, Yobe, and Jigaya and started coming down to the Sudan Savannah. The years 1983 and 1987 were particular with almost the whole country being affected (Sahel and Savannah zones) with 12 incidence of HW in the Sahel. The Southern part (Coastal and Tropical Rainforest zones) was particularly affected from 1996 to 2005 and had a peak of 5 events. Like in the previous observations, HWN using EHF reached the highest peak in 2007 with 16 events in the East, Northern and Southern part of Adamawa State, see Figure 4.5a,b.

All the three HW definitions (TN90, TX90 and EHF) revealed almost the same pattern of HWN in Nigeria from 1981 to 2016 showing peaks in 1983, 1987, 1997, 2006 and 2007, the latter had the highest number of events. The general coverage of the number of events increased from 1999.

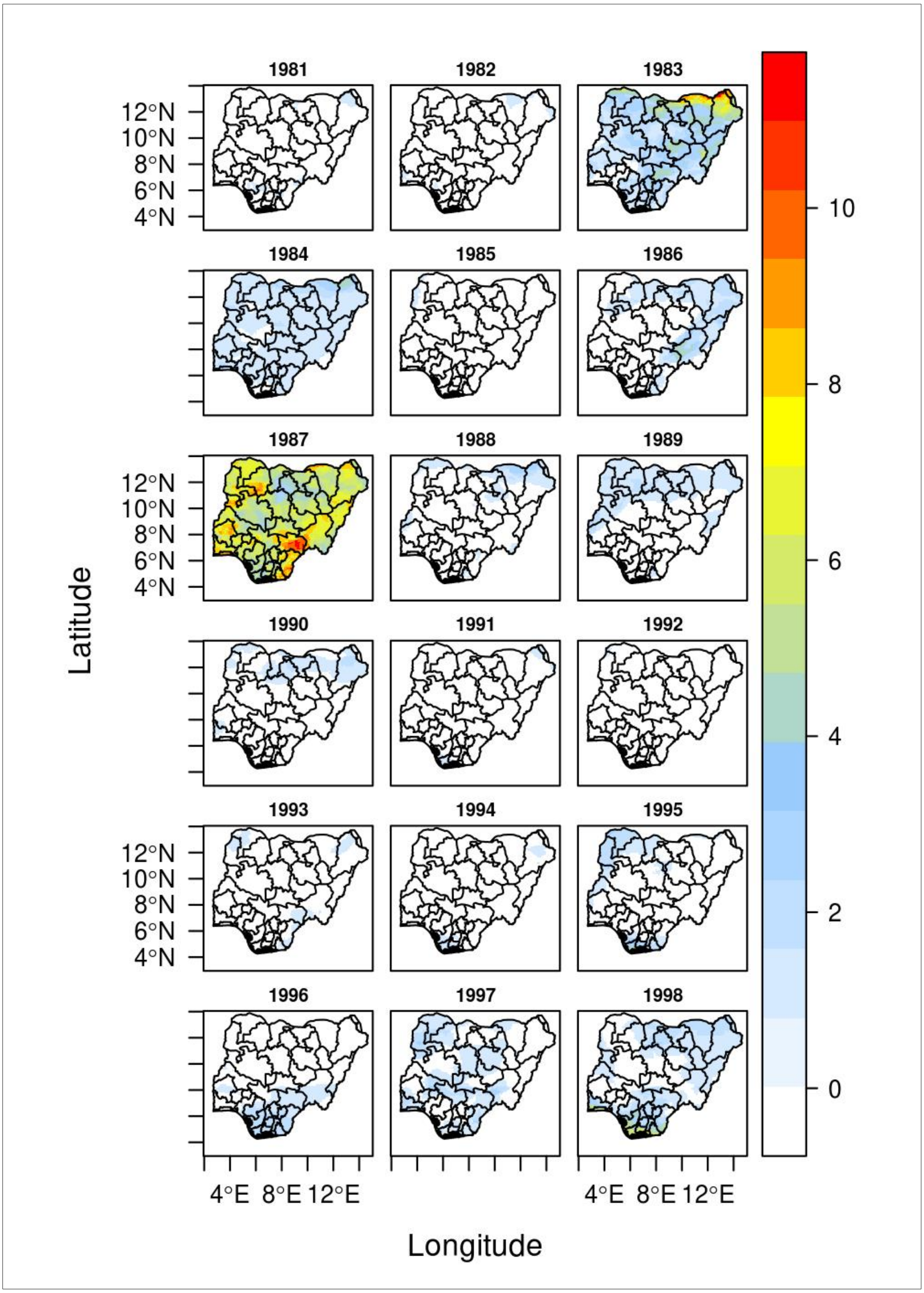

Figure 4.5a Heat Wave Number (HWN) for EHF; 1981-1998

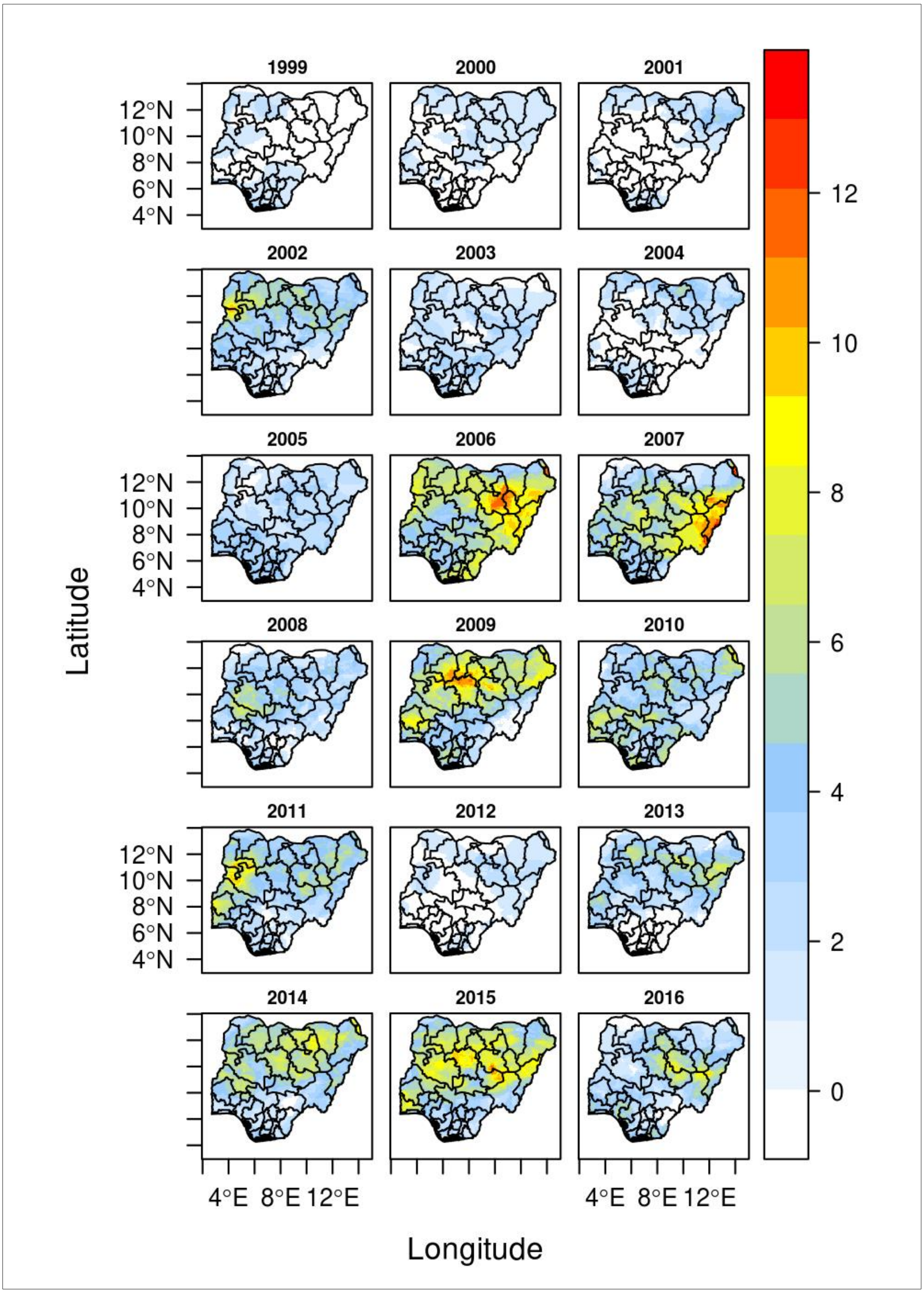

Figure 4.5b Heat Wave Number (HWN) for EHF; 1999-2016

4.2.2.2 Heat Wave Duration (HWD) for TX90, TN90 and EHF

Heat Wave Duration (HWD) is the extent in days of the most prolonged heatwave defined by HWN. For TX90 HWs, the duration varied from 1 to 25 days for the longest HW of the period 1981-2016. In 1983, the Sahel recorded 18 days and the Sudan Savannah 5 to 10 days. The Tropical Rainforest and the Coastal zones recorded less than 3 days. Sokoto had 21 days in 1984. The year 1987 in Figure 4.6a,b also recorded 14 days in Yobe and Borno and 11 in Kaduna, Zamfara and some parts of Plateau State. Cross River in 1996 had 8 days of HW. In 2008 the central part (Sudan Savannah), with Niger State, especially around Minna was affected by a 14 days HW while the Eastern part of the State had 12 days HW in 2014.

For TN90 HWs, the Figure 4.7a,b showed that 1983 and 1987 recorded different duration across the country and the different climatic zones. The year 1983 recorded the highest duration (12 days) between Kaduna and Niger State in the Sahel while the South (Western part in Ogun and Cross River) was having the highest HWD with 20 days. The years 1990s were very low (2 to 8 days) but in 2000s more areas were affected by HWs of 8-10 days. For example, in 2009 Borno was affected by 16 days and in 2015 the South has been covered by 10 to 15 days HW.

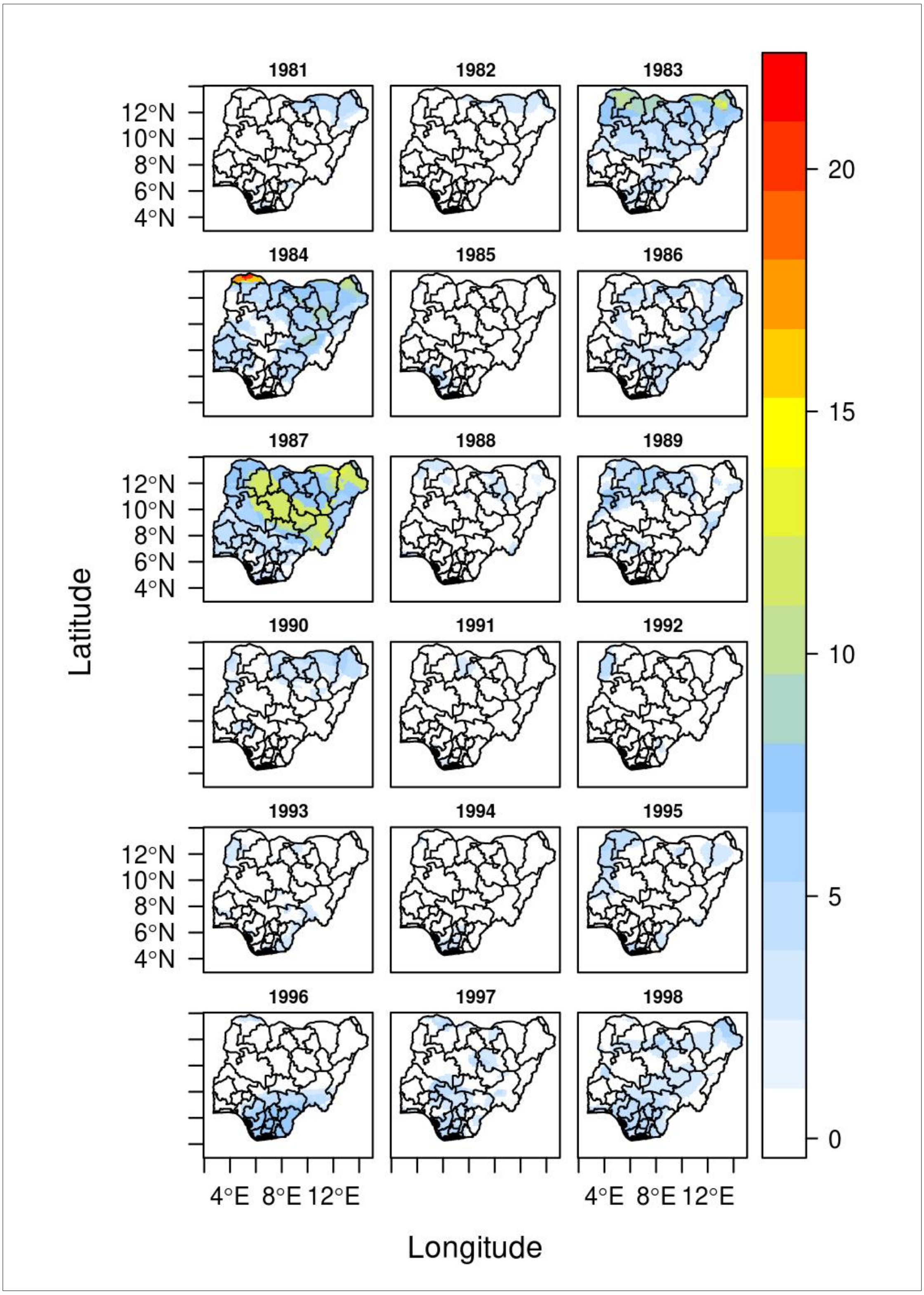

Figure 4.6a Heat Wave Duration (HWD) for TX90; 1981-1998

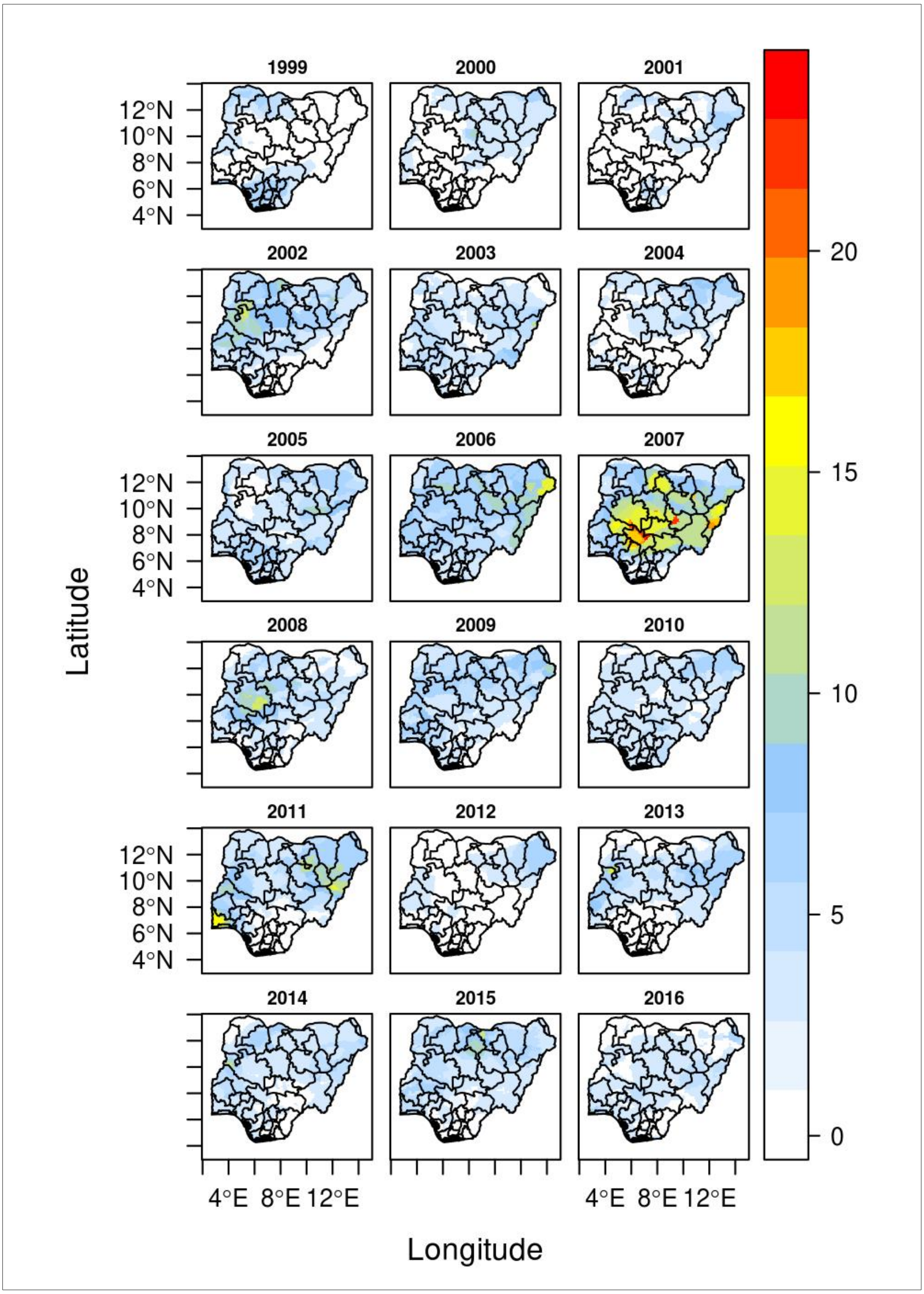

Figure 4.6b Heat Wave Duration (HWD) for TX90; 1999-2016

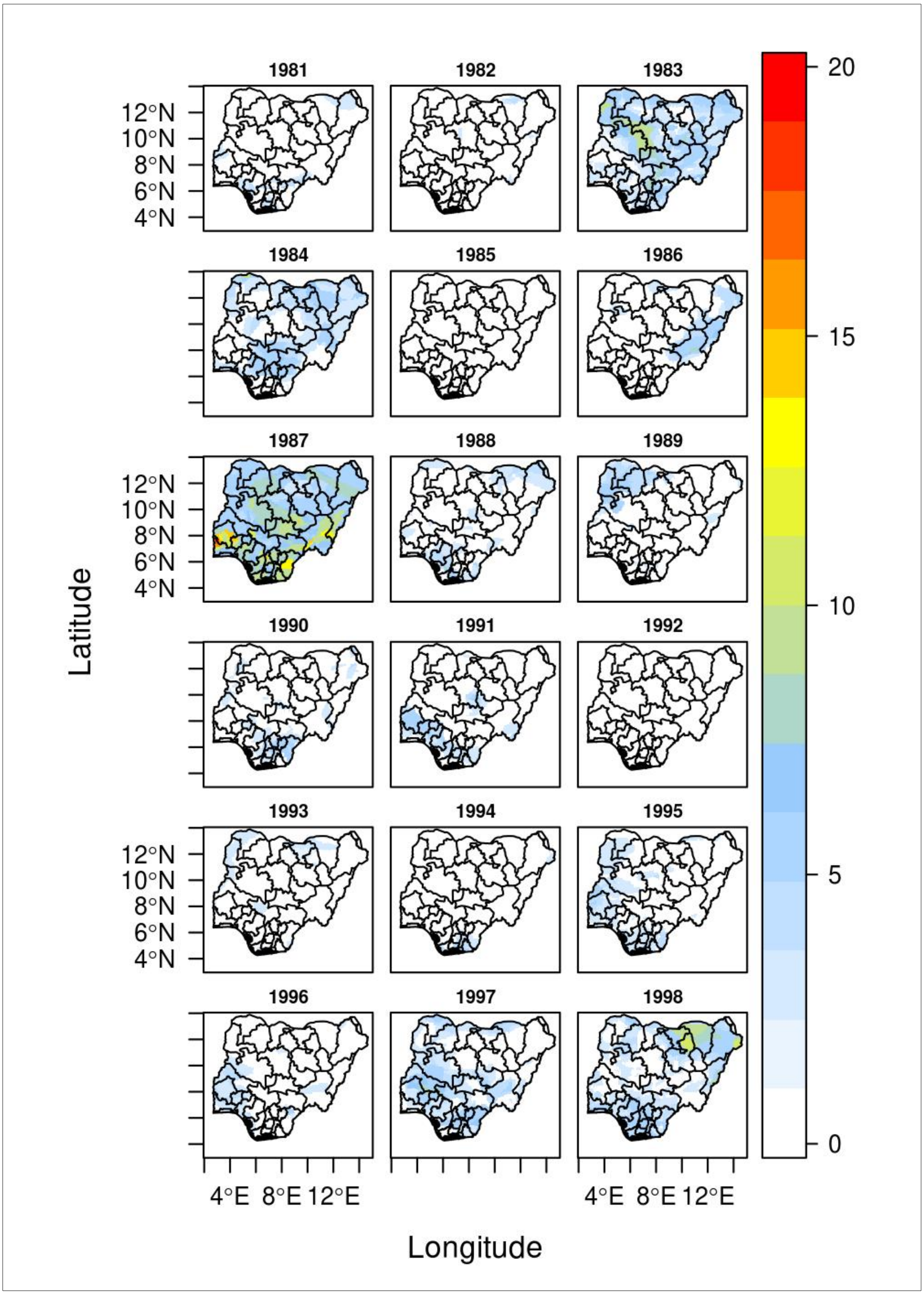

Figure 4.7a Heat Wave Duration (HWD) for TN90; 1981-1998

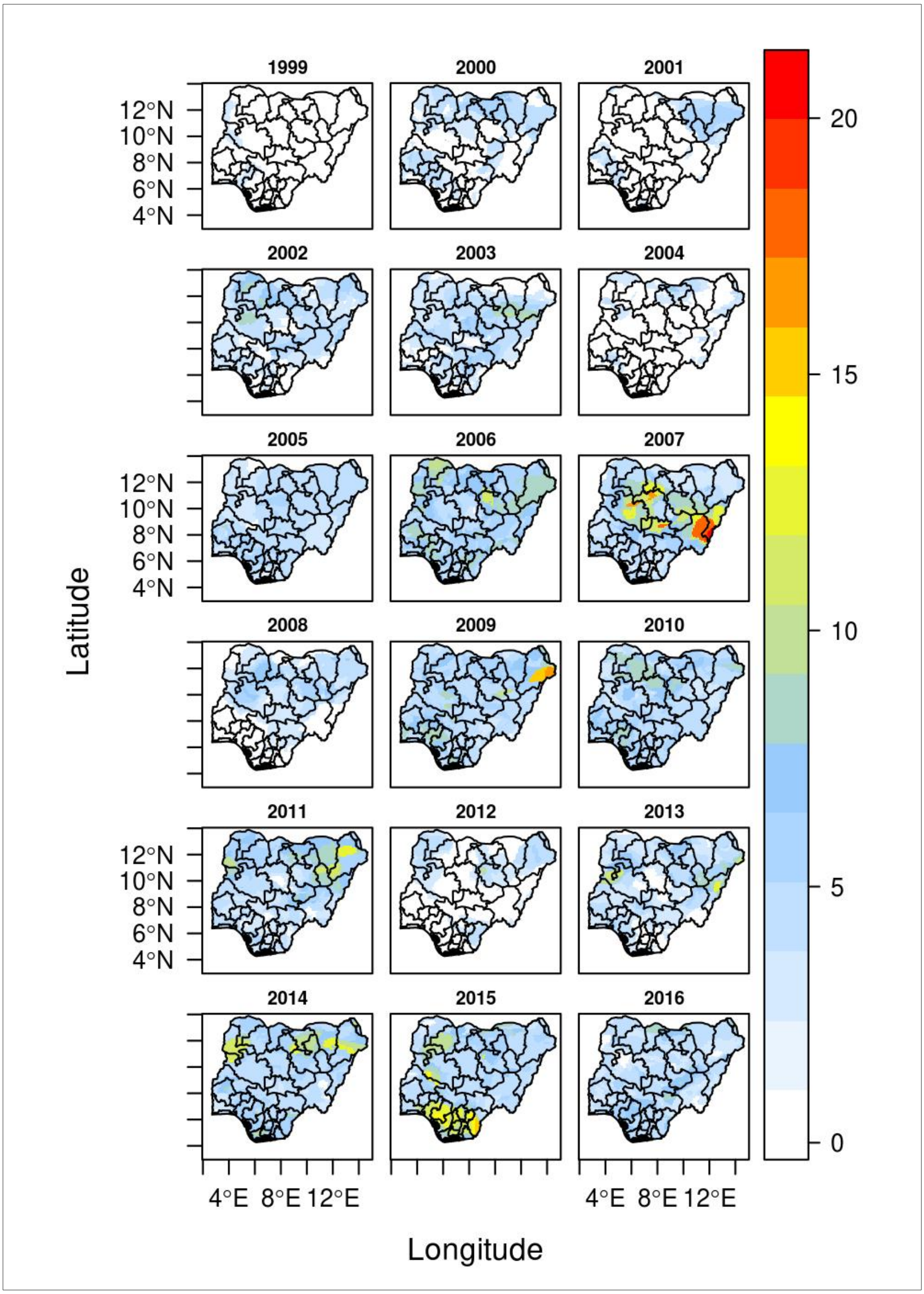

Figure 4.7b Heat Wave Duration (HWD) for TN90; 1999-2016

The same results were obtained with HWD for EHF, where 1983 was having 20 days in the Sahel and 5 to 10 days in the Sudanian zone (Figure 4.8a,b). Borno was the most affected but the spatial coverage was very small in the State. In 1987 the Northern and North Centrale Nigerian States of Zamfara, Kaduna, Kano, Bauchi and Plateau had 8-13 days of the longest EHF HWs. The Guinea and Sudan Savannah hardly had 4 days in the 1980s and 1990s till 1996 where the South was having 8 days especially in Cross River, parts of Kwara and Rivers States. In 2007, Kogi and Abuja Federal Capital Territory (FCT) recorded 35-50 days and 2008 was Minna phase in Niger State with 17 days.

The general occurrence of HWs varied between 0 and 20 days. The higher numbers were found everywhere in the country independent of the temperature distribution, especially with EHF.

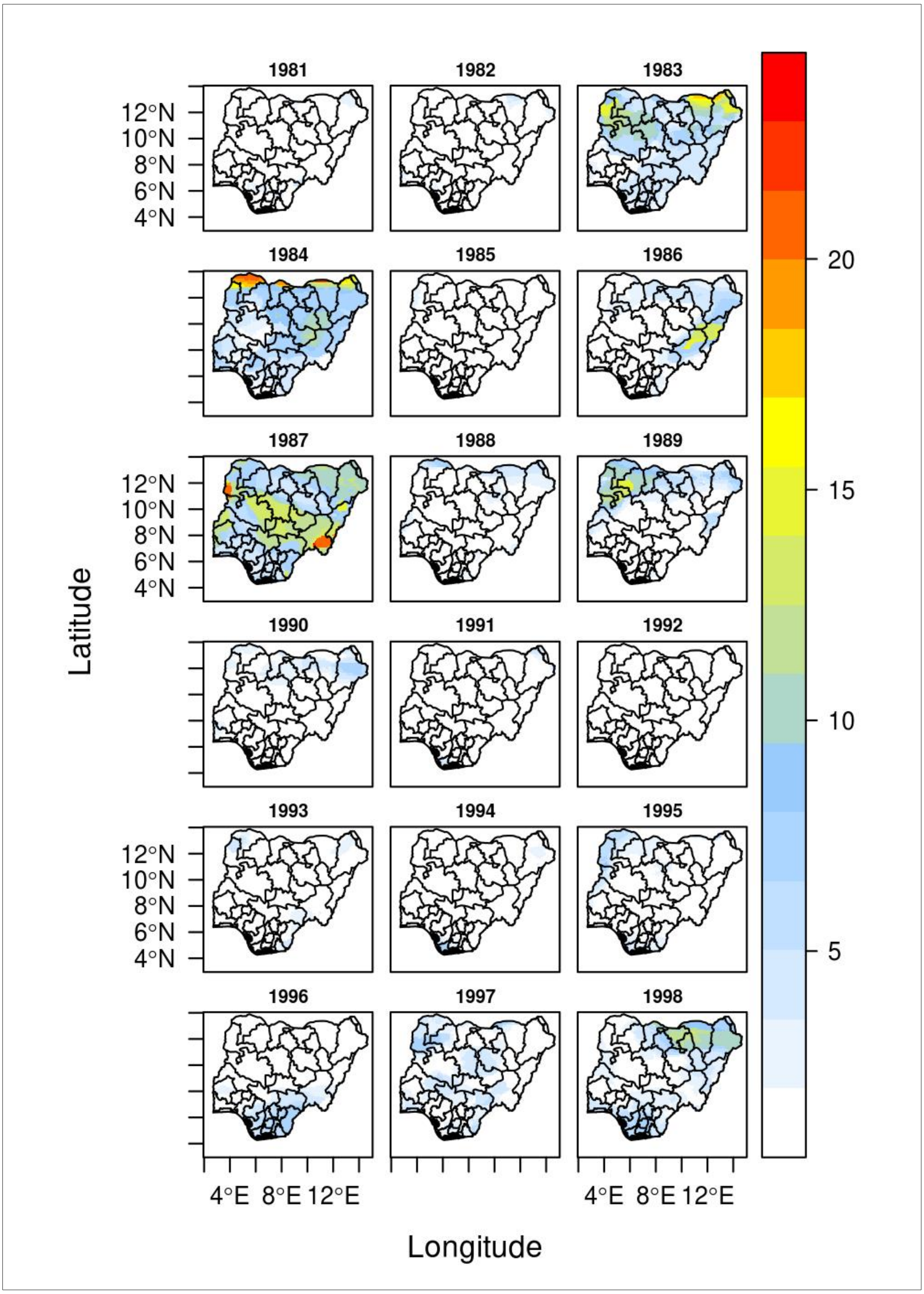

Figure 4.8a Heat Wave Duration (HWD) for EHF; 1981-1998

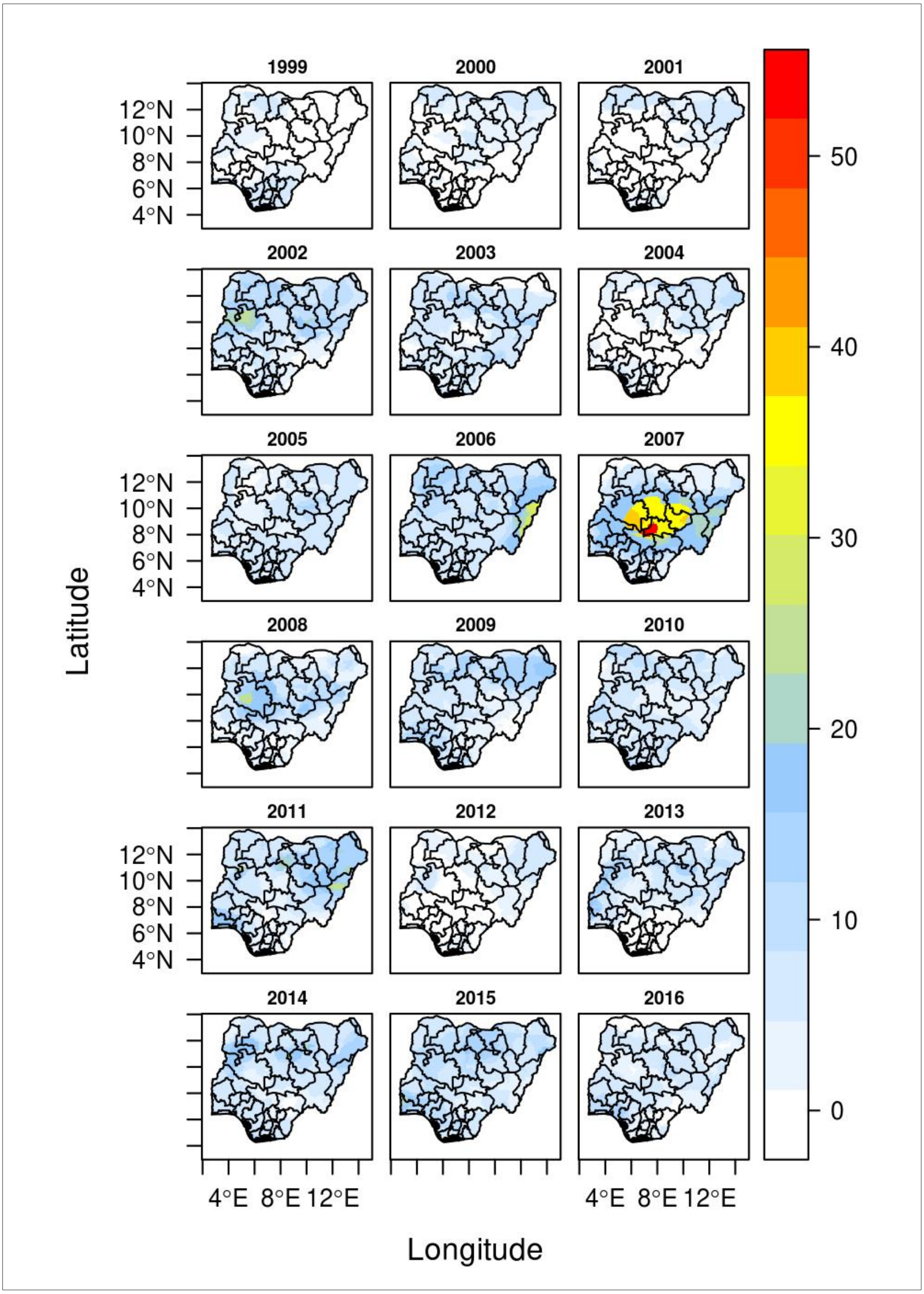

Figure 4.8b Heat Wave Duration (HWD) for EHF; 1999-2016

4.2.2.3 Heat Wave Frequency (HWF) for TX90, TN90 and EHF

HW Frequency (HWF) is the number of days that contribute to HWs defined by HWN (HW days). For HWs that begin before the period of interest (in the Northern hemisphere it includes May to September), only the HW days within the period of interest were recorded. For HWs that extend beyond the period of interest, a maximum of 14 days beyond the period of interest were added. The TX90 recorded a peak of ~ 85 days in 2006 and 2007 (Figure 4.9a,b) in the Eastern part of Nigeria covering all Borno and Adamawa States. The years 1983 and 1987 reached 45 and 55 days respectively in Borno and Yobe. From 1996 the coastal and tropical rainforest recorded 10 to 15 days in Cross River, Bayelsa, Rivers and Delta. Niger State experienced in 2002, 45 days HW. From 2007, the frequency has been increasing with an average of 30 days except for 2012 where it was low. This high frequency of HW in Niger State might be due to the high temperatures. It has also been observed with ERA-Interim reanalysis data, high precipitation records in the area in 2002 and some high records of precipitation in 2012.

Taking into account a possible correlation between the maximum and minimum temperature, the results of HWF for TX90 are similar to the one of HWF for TN90. Effectively, peaks of 38 and 55 days were observed in 1983 in the Sahel (Borno) and in 1987 from the Coastal to Tropical Rainforest respectively covering part of Guinea Savannah in Benue, Cross River, Osun, Ekiti, Edo and Delta States. A frequency of 70 days has been observed in 2006 and 2007 in the Guinea and Sudan Savannah zones in the East, covering Bauchi, Gombe, Adamawa and Southern Borno in the Guinea and Savannah zones and also in Zamfara and Sokoto in the West of Sahel. The Sahel was submerged by a 38 days HW in 2011 and a 40 to 50 days in 2014 (Figure 10a,b).

There is a spatial increase in the highest values of HWF in Nigeria from 2005. The EHF shows in Figure 4.11a,b the same results like the TX90 and the TN90. In 1983 and 1987, the frequency reached 50-70 days in the extreme North East and 45 to 50 days in all the climatic zones respectively. The period 2005-2010 had the highest HWF in the East (Adamawa and Borno). During the years 2006 and 2007 were observed the highest HWF of the whole period with frequencies reaching 100 days in the Eastern part of Guinea and Sudan Savannah.

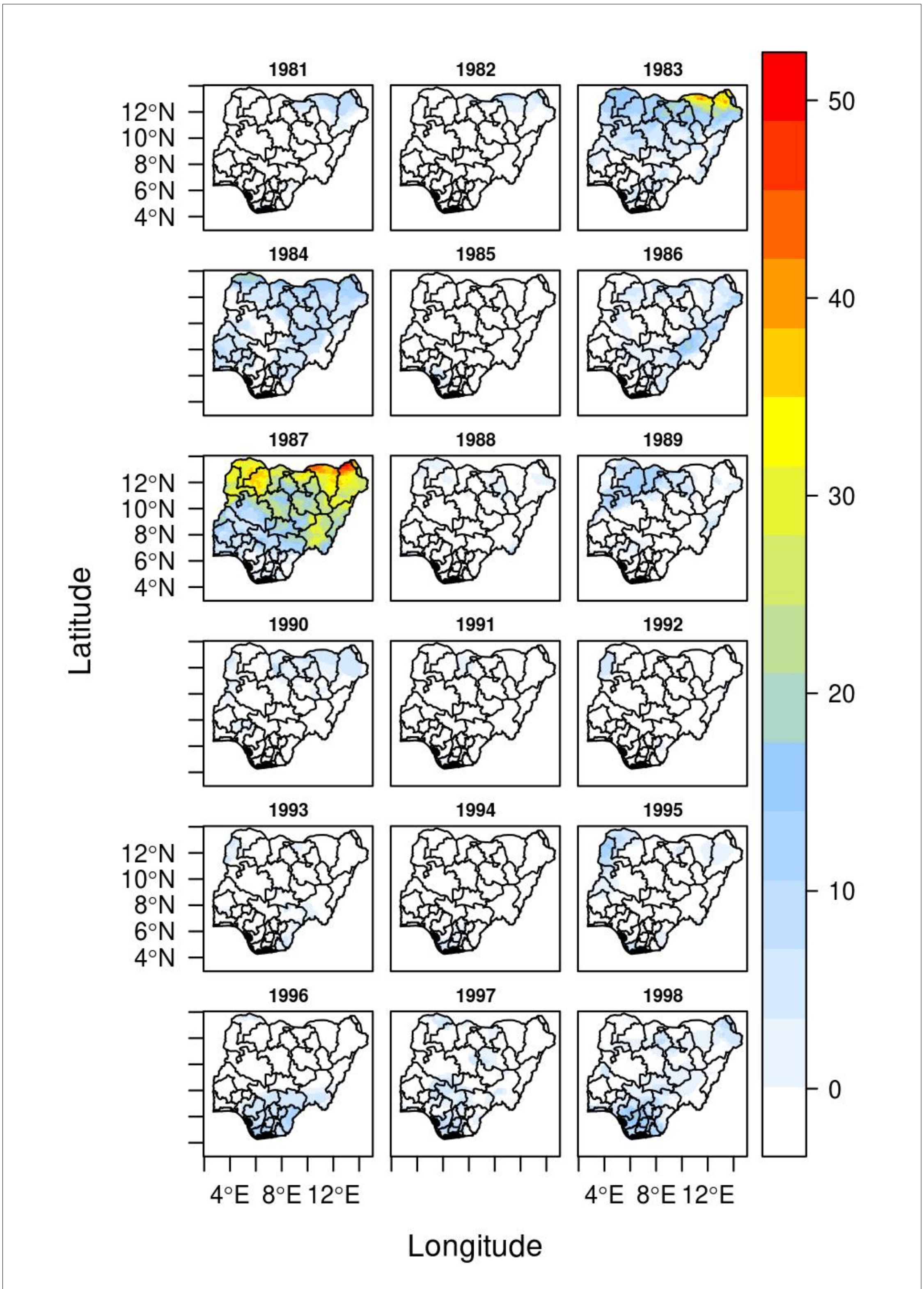

Figure 4.9a Heat Wave Frequency (HWF) for TX90; 1981-1998

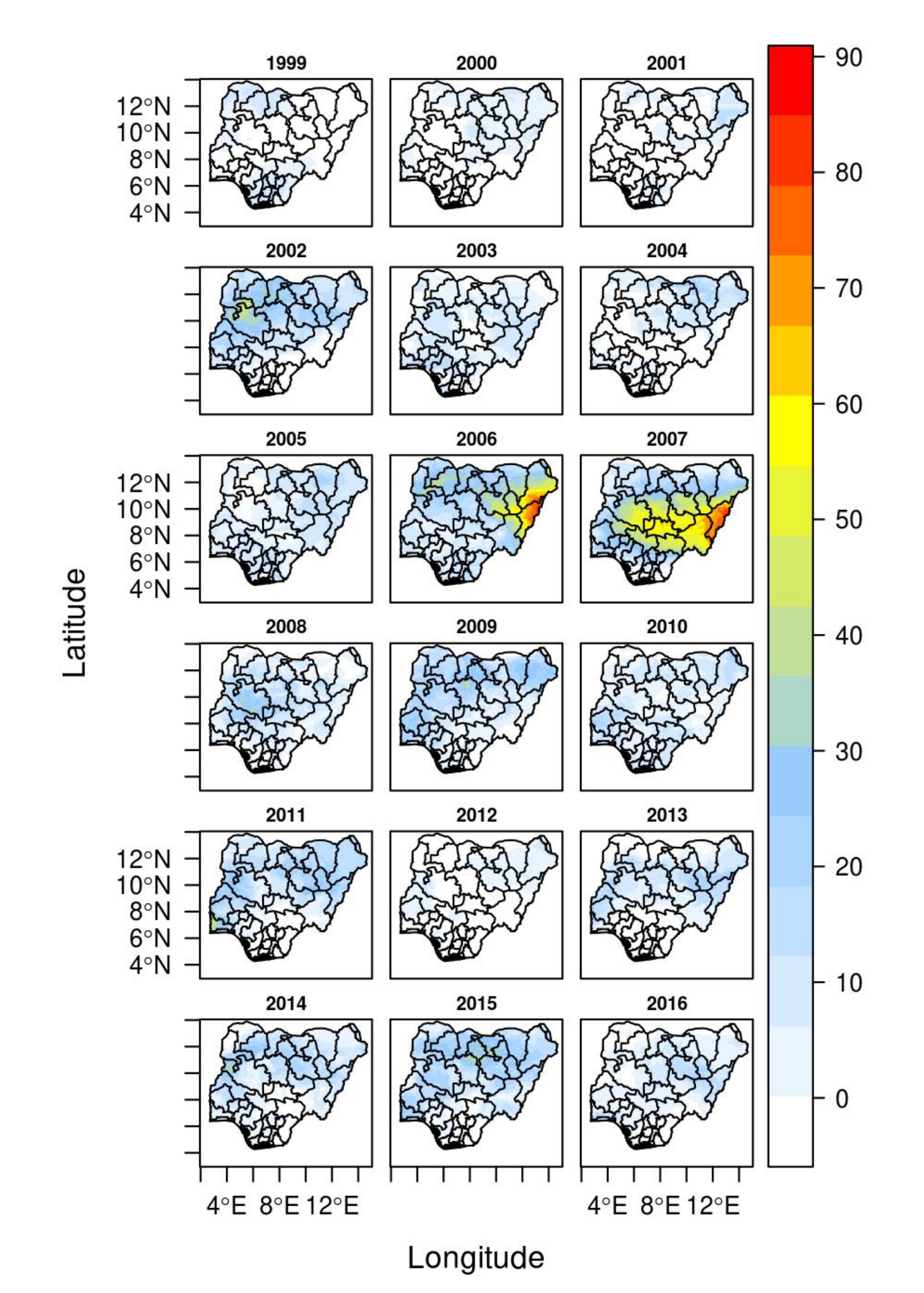

Figure 4.9b Heat Wave Frequency (HWF) for TX90; 1999-2016

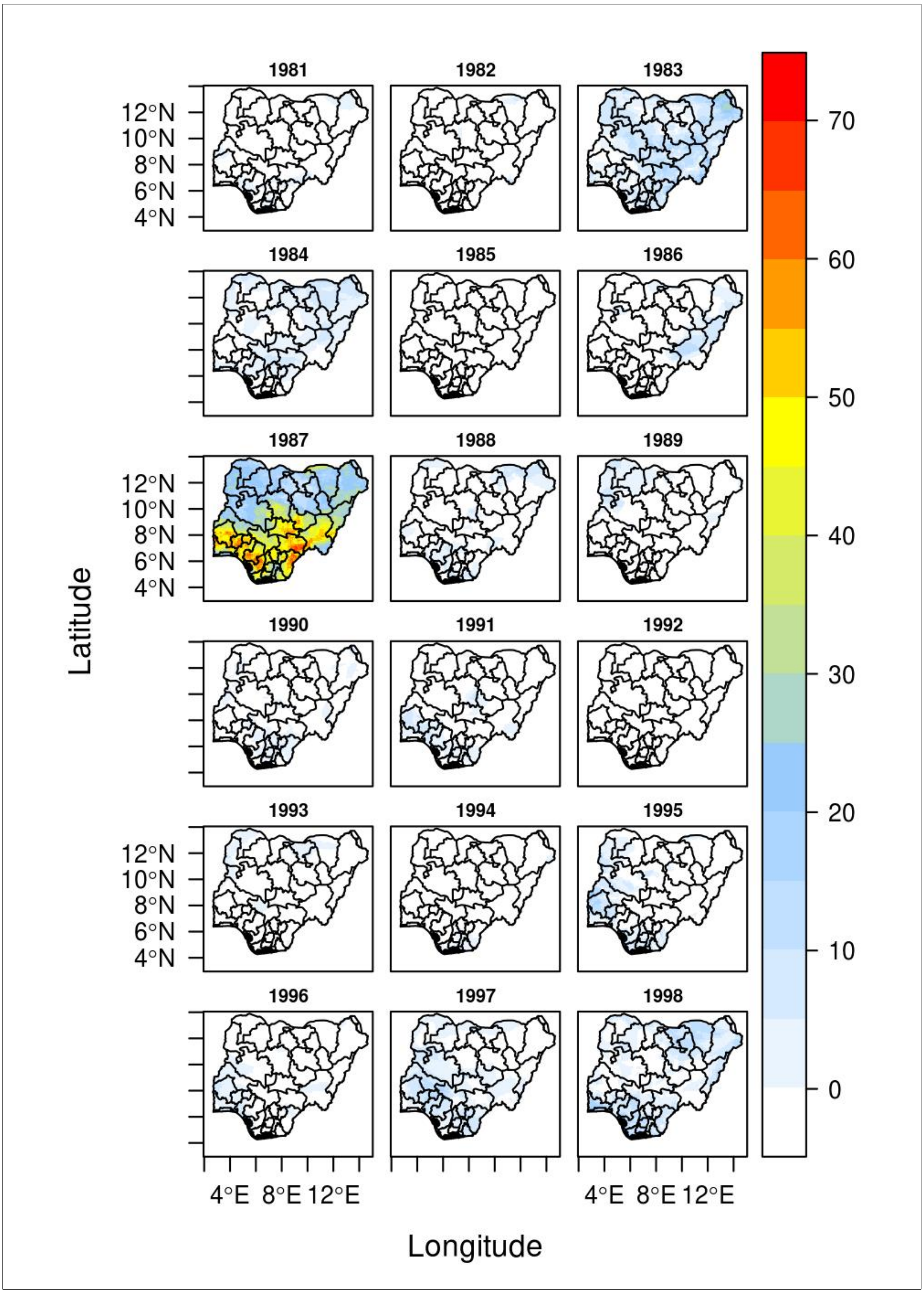

Figure 4.10a Heat Wave Frequency (HWF) for TN90; 1981-1998

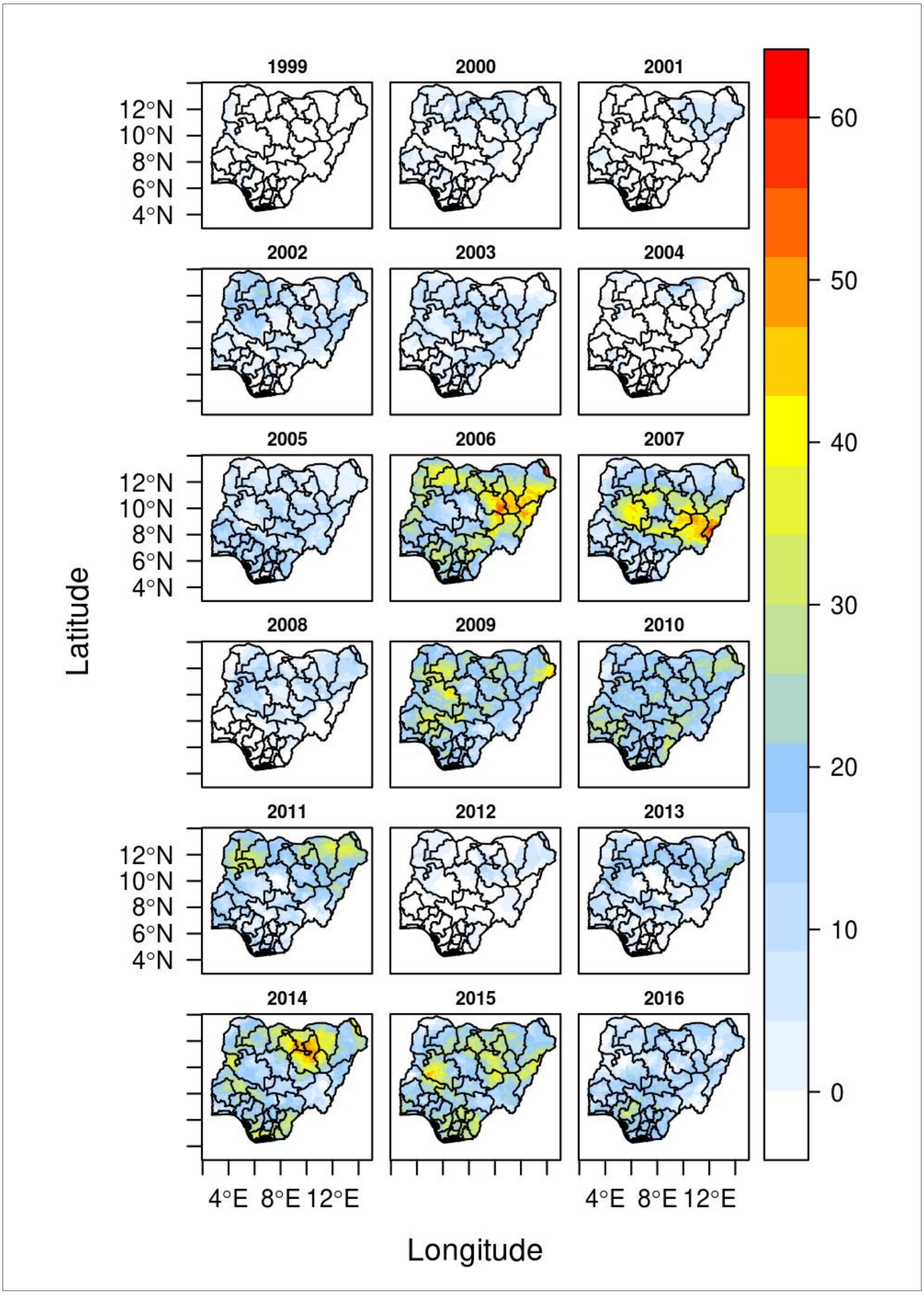

Figure 4.10b Heat Wave Frequency (HWF) for TN90; 1999-2016

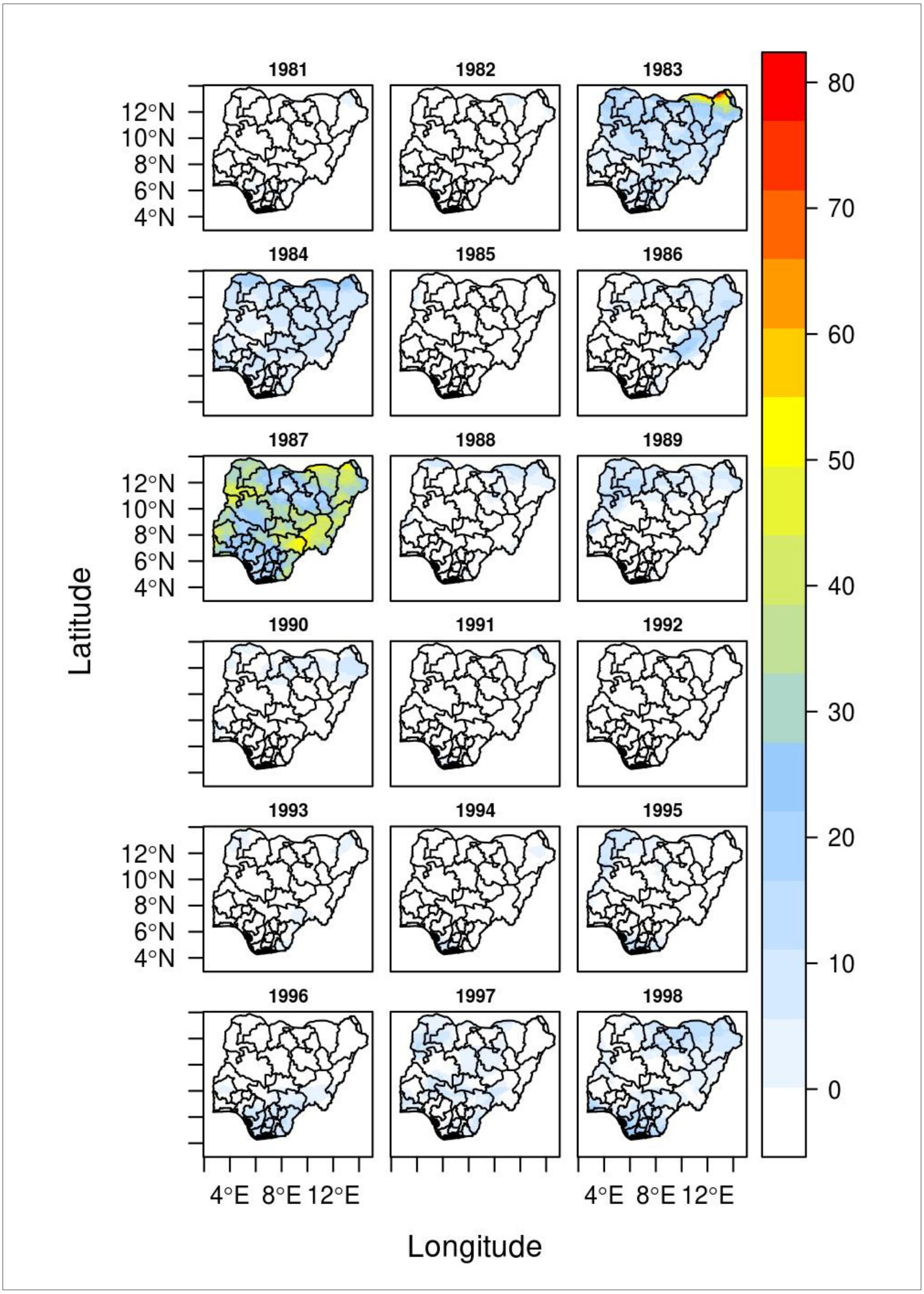

Figure 4.11a Heat Wave Frequency (HWF) for EHF; 1981-1998

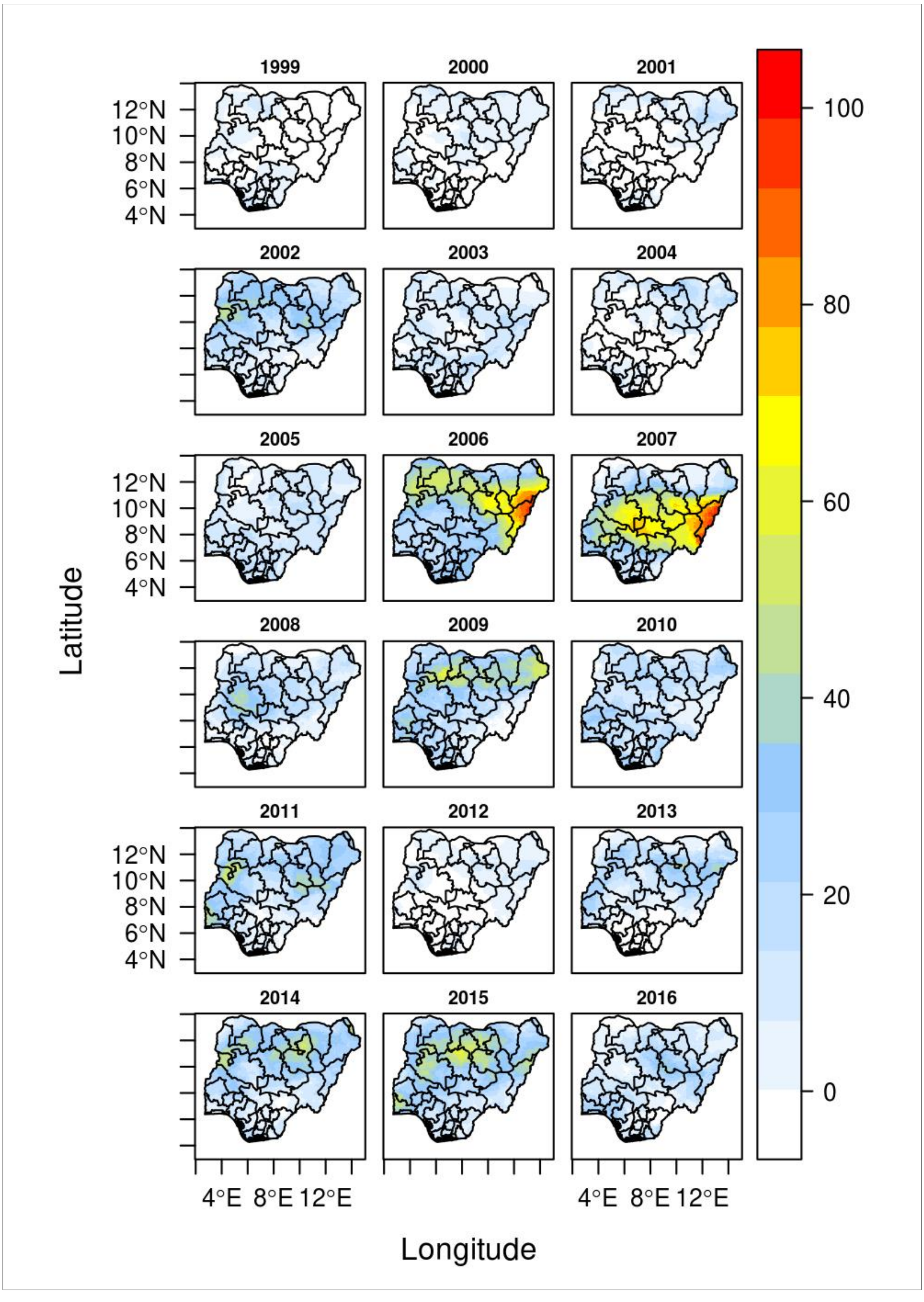

Figure 4.11b Heat Wave Frequency (HWF) for EHF; 1999-2016

4.2.2.4 Heat Wave Magnitude (HWM) and Heat Wave Amplitude (HWA) for TX90, TN90, EHF and HWMId

Heat Wave Magnitude (HWM) is the mean of the mean HW days of each HW defined by HWN and the HW Amplitude (HWA) is the extreme daily measure of the hottest HW (defined as the HW with the highest magnitude). Regarding TX90, the years 1980's had an average HW of magnitude 35 °C and 45 °C was the general peak in the Sahel for the period under consideration. In 1985 the occurrence of HW was spatially small and found only in Kebbi and Yobe. The amplitude of the year was almost the same value as the magnitude, 30 °C to 45 °C. In the 1990s, HW was located only in the Sahel and the magnitude varied from 35 to 45 °C, same as the amplitude. The Sudan Savannah zone did not experience important HWs during the 90s but the Coastal and Tropical Rainforest zones had some lower magnitude of 25 to 30 °C. In the Sahel the HWs were observed more in the South East of the zone. From 2002 the coverage of HWs was extended countrywide, but the amplitude and magnitude follows the same pattern as the temperature. The Sahel had the highest magnitude and amplitude superseded by Sudan Savannah, Guinea Savannah, Tropical rainforest and the Coastal zone came last. The same pattern was observed during the latest years 2007-2016. In Figure 4.12a,b and Figure 4.13a,b, a variation in the spatial coverage of HWs of amplitude and magnitude 35-40 °C was observed but there is no clear increasing trend.

The magnitude and amplitude of TN90 show the same pattern over the years, but they are lower than the ones observed in TX90 (Figure 4.14a,b and Figure 4.15a,b). This is normal if we assume that there is a correlation between the TX and TN and always TX > TN.

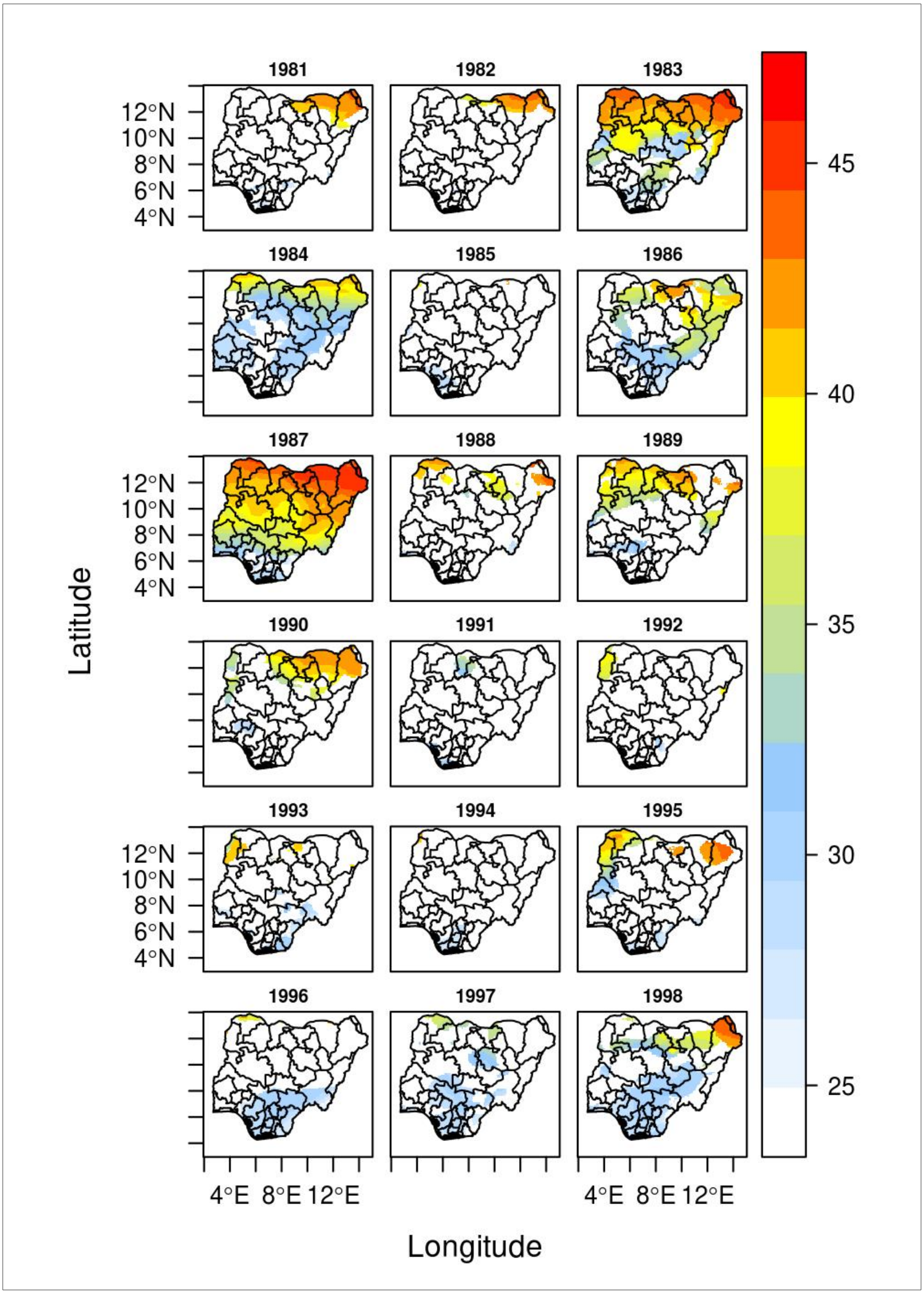

Figure 4.12a Heat Wave Amplitude (HWA) for TX90; 1981-1998

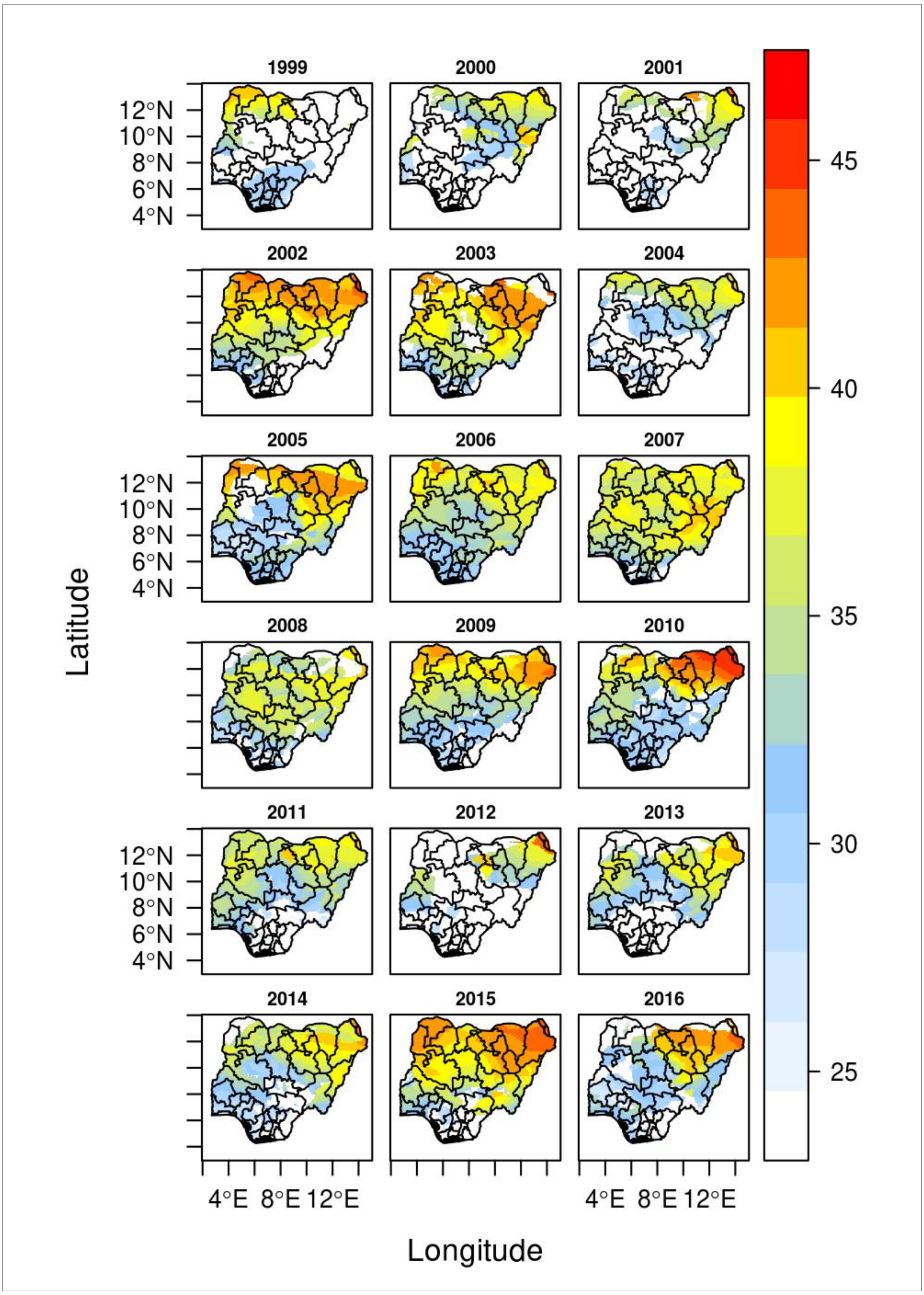

Figure 4.12b Heat Wave Amplitude (HWA) for TX90; 1999-2016

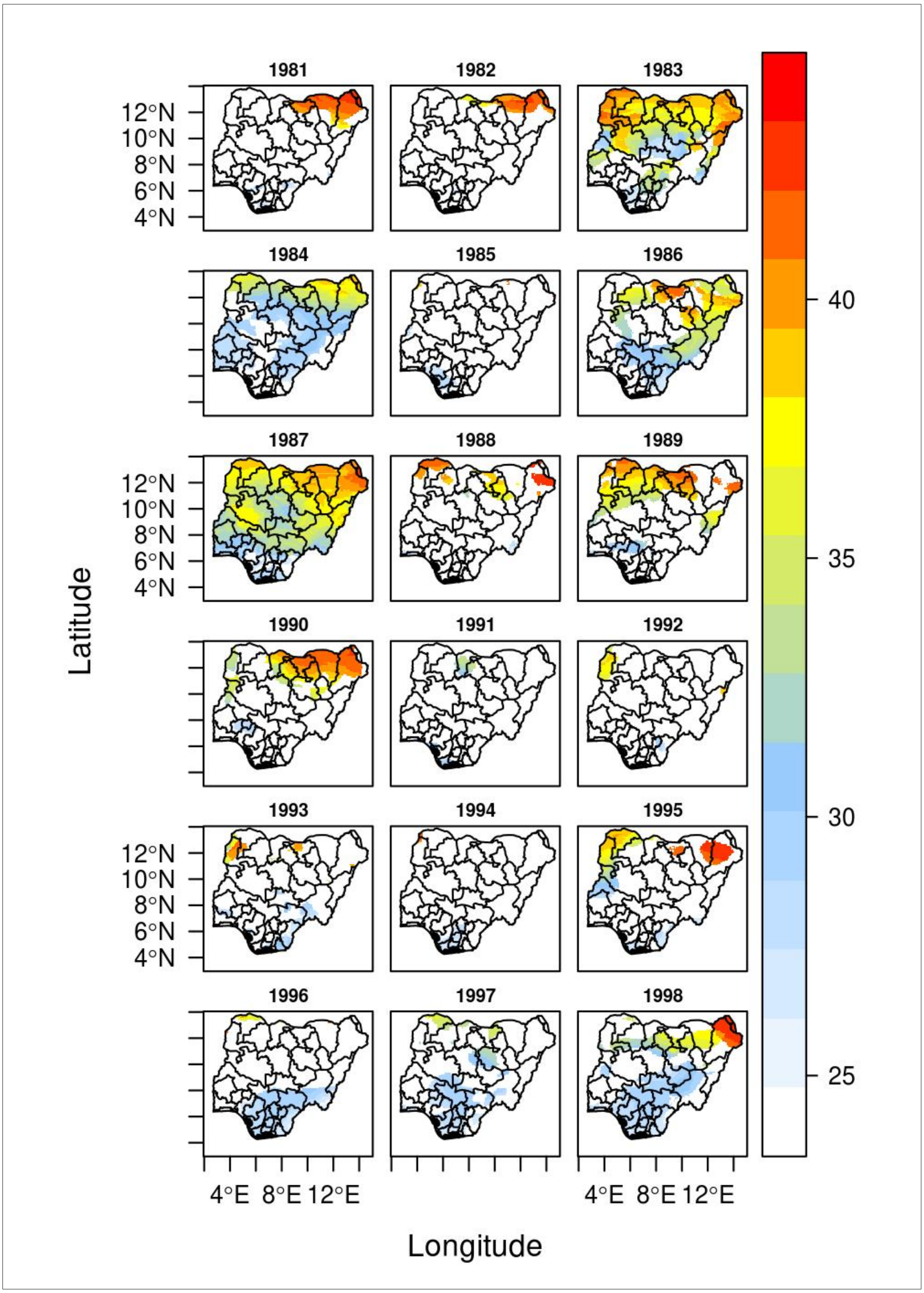

Figure 4.13a Heat Wave Magnitude (HWM) for TX90; 1981-1998

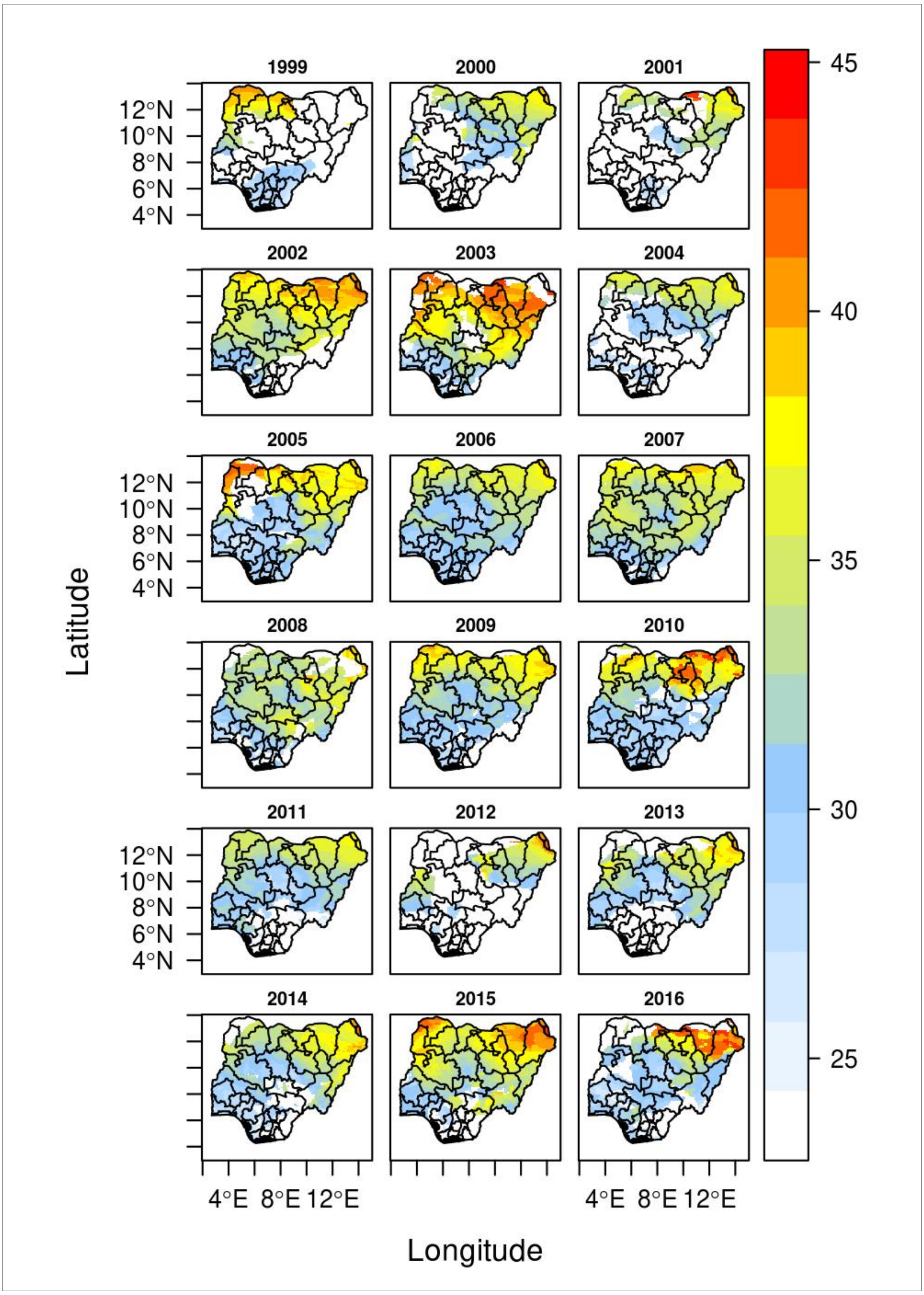

Figure 4.13b Heat Wave Magnitude (HWM) for TX90; 1999-2016

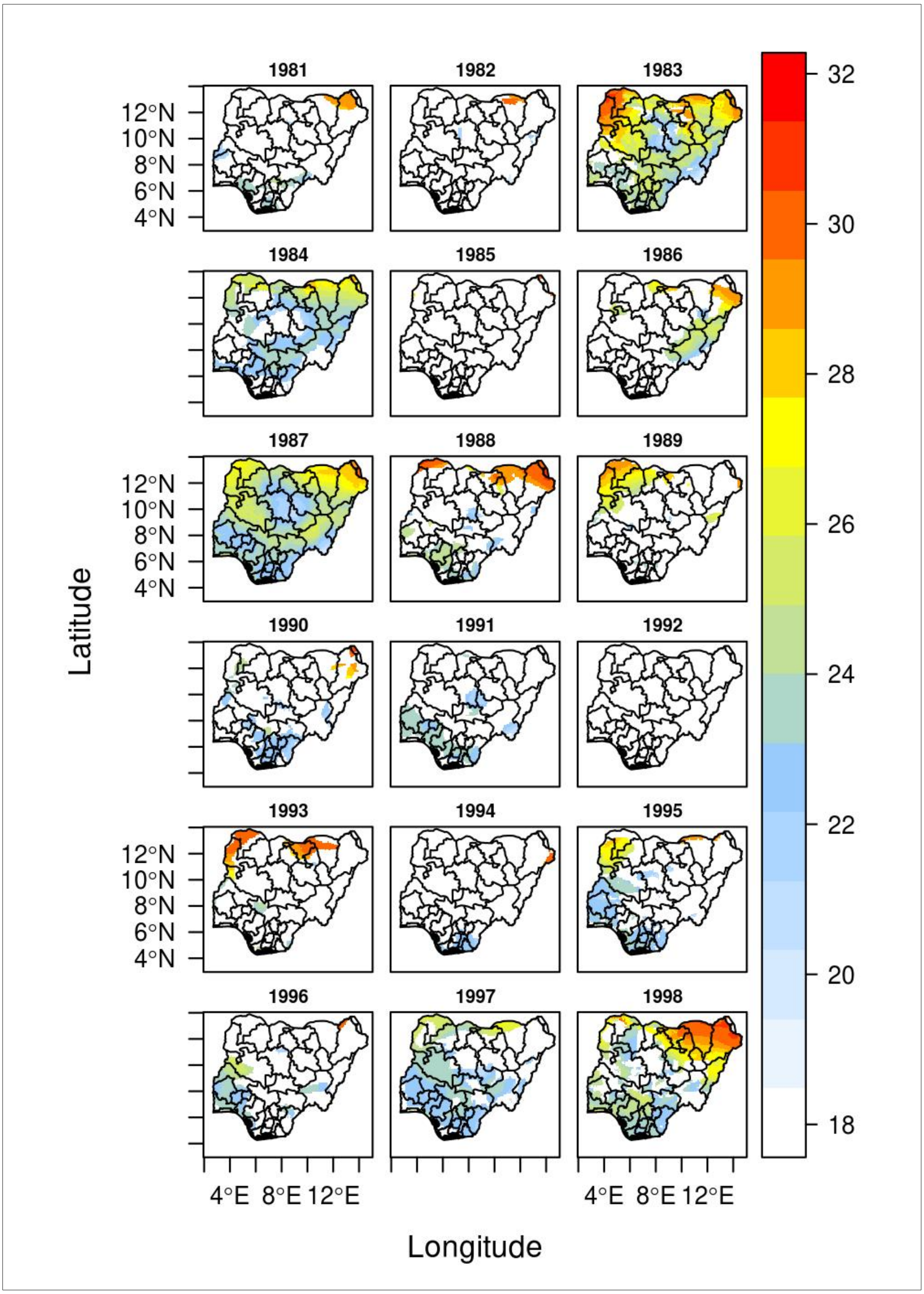

Figure 4.14a Heat Wave Magnitude (HWM) for TN90; 1981-1998

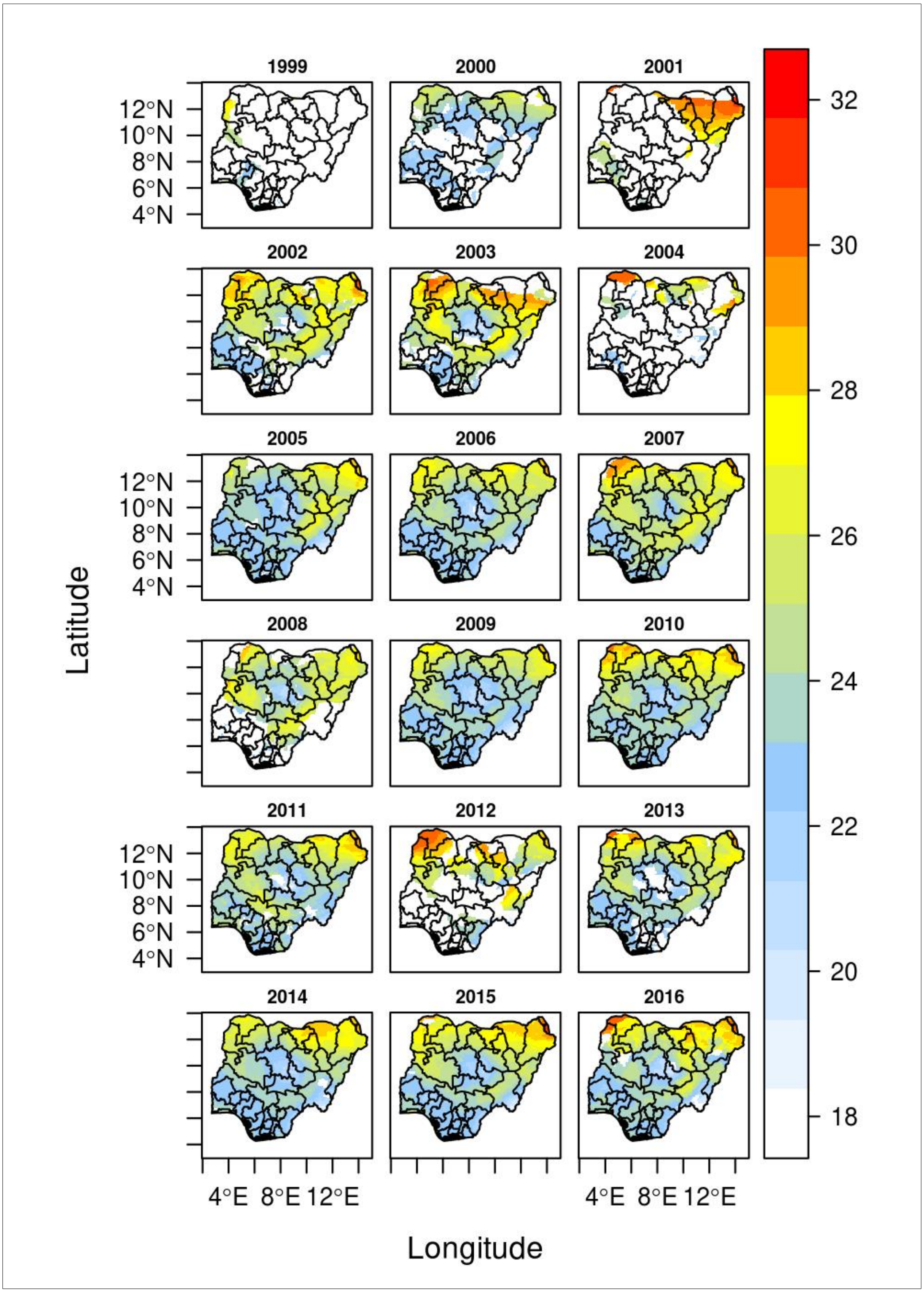

Figure 4.14b Heat Wave Magnitude (HWM) for TN90; 1999-2016

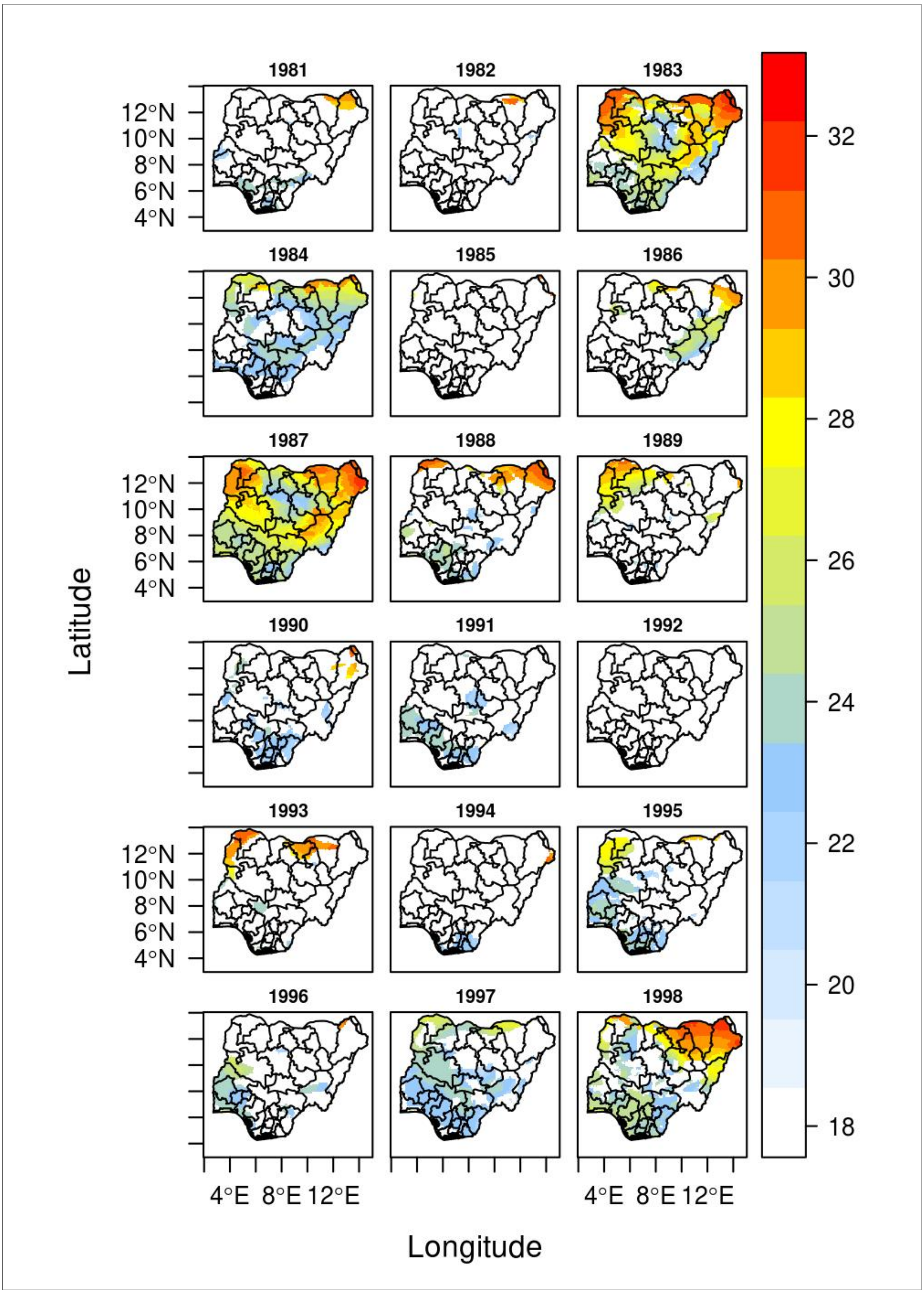

Figure 4.15a Heat Wave Amplitude (HWA) for TN90; 1981-1998

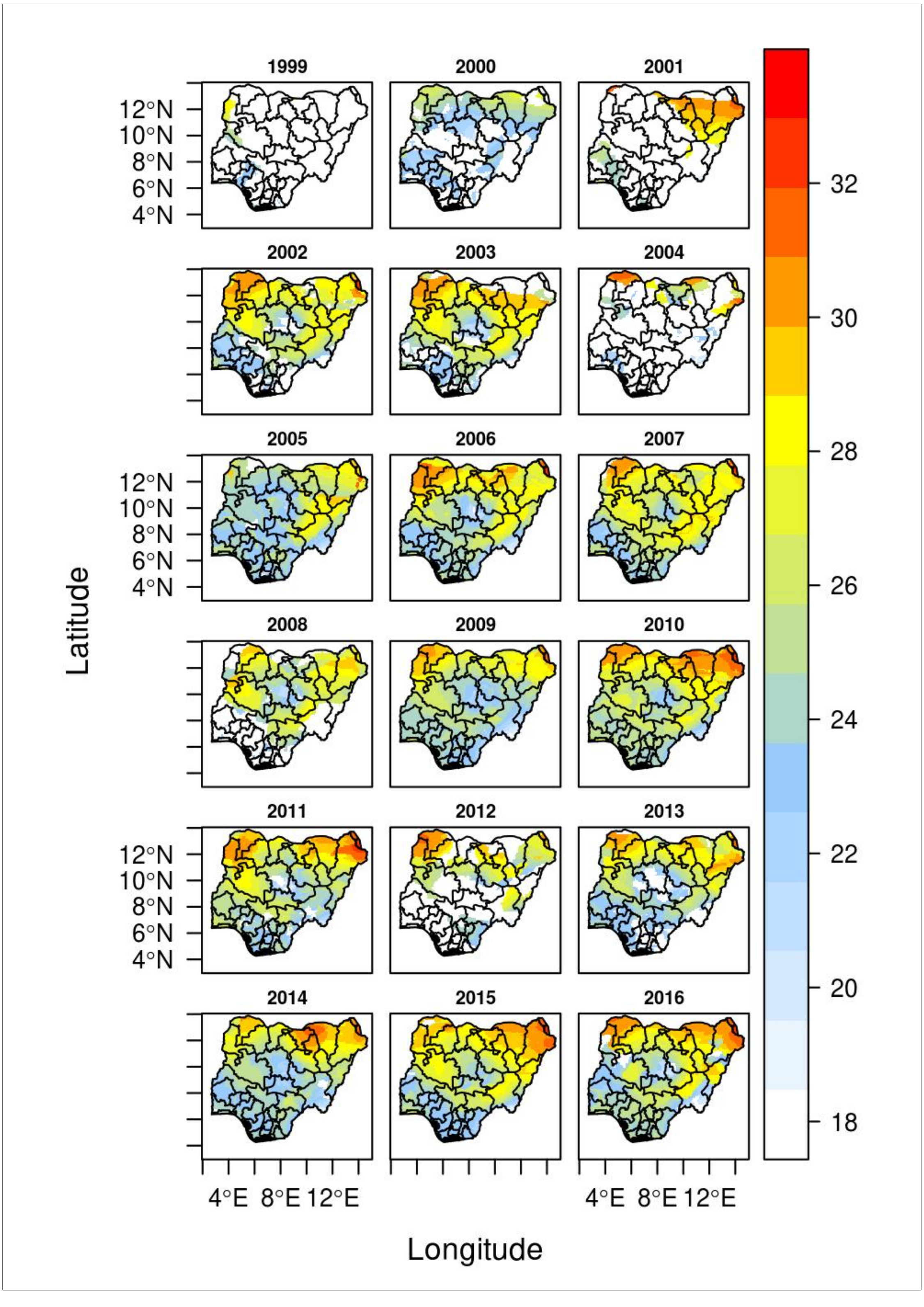

Figure 4.15b Heat Wave Amplitude (HWA) for TN90; 1999-2016

The HWM for EHF in Figure 4.17a,b is similar to the HWM for TX90. The high magnitudes are mainly located in the Sahel where an increase in the magnitude had occurred from 2005. The magnitude varies from 25 $°C^2$ in the South (Coastal and Tropical Rainforest) to 45 $°C^2$ in the Sahel and some parts in the Savannah zones (especially the East). In 1983, the HW was severe in the Eastern part of the Sahel (8-11 $°C^2$), and the rest of the country experienced HW of average magnitude 4 $°C^2$. In 1987, there was a countrywide prevalence of HWM of 7 to 11 °C average where the peak (11$°C^2$) occurred in Benue State in the Guinea Savannah. Then 2002, 2006, 2007, 2009, 2011, 2014 and 2015 recorded high HWM especially in the Sudan Savannah, the Sahel and the East of Nigeria. The years 1987, 2006 and 2007 has the highest records of HWM in the present time.

The HWM results obtained in this analysis were compared to a robust index that is the Heat Wave Magnitude Index daily (HWMId) (Russo *et al.*, 2015; Russo *et al.*, 2016; Ceccherini *et al.*, 2016a,b; Dosio, 2016). The HWMId is the highest annual magnitude of HWs. HW is then defined as a succession of 3 or more days in which the TN/TX is above the 90th percentile of daily TN/TX for a 31-day running window of this day during the reference period (1980-2011). The Index integrates several climate-related measurements of aggravated heat into a number that enables to compare HWs that came to pass in various regions and in different years (Russo *et al.*, 2014, 2015, 2016; Ceccherini *et al.*, 2016a,b).

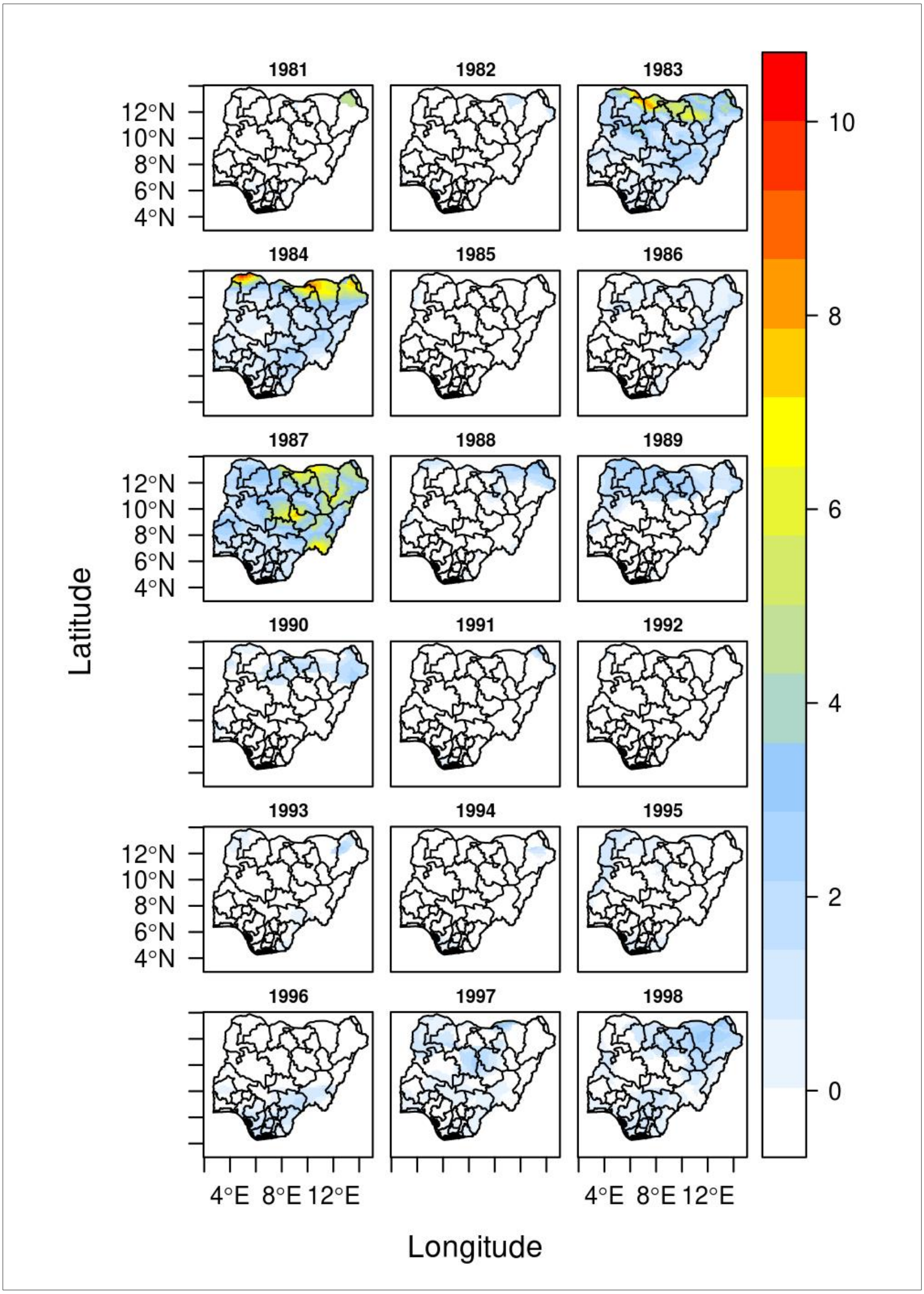

Figure 4.16a Heat Wave Amplitude (HWA) for EHF; 1981-1998

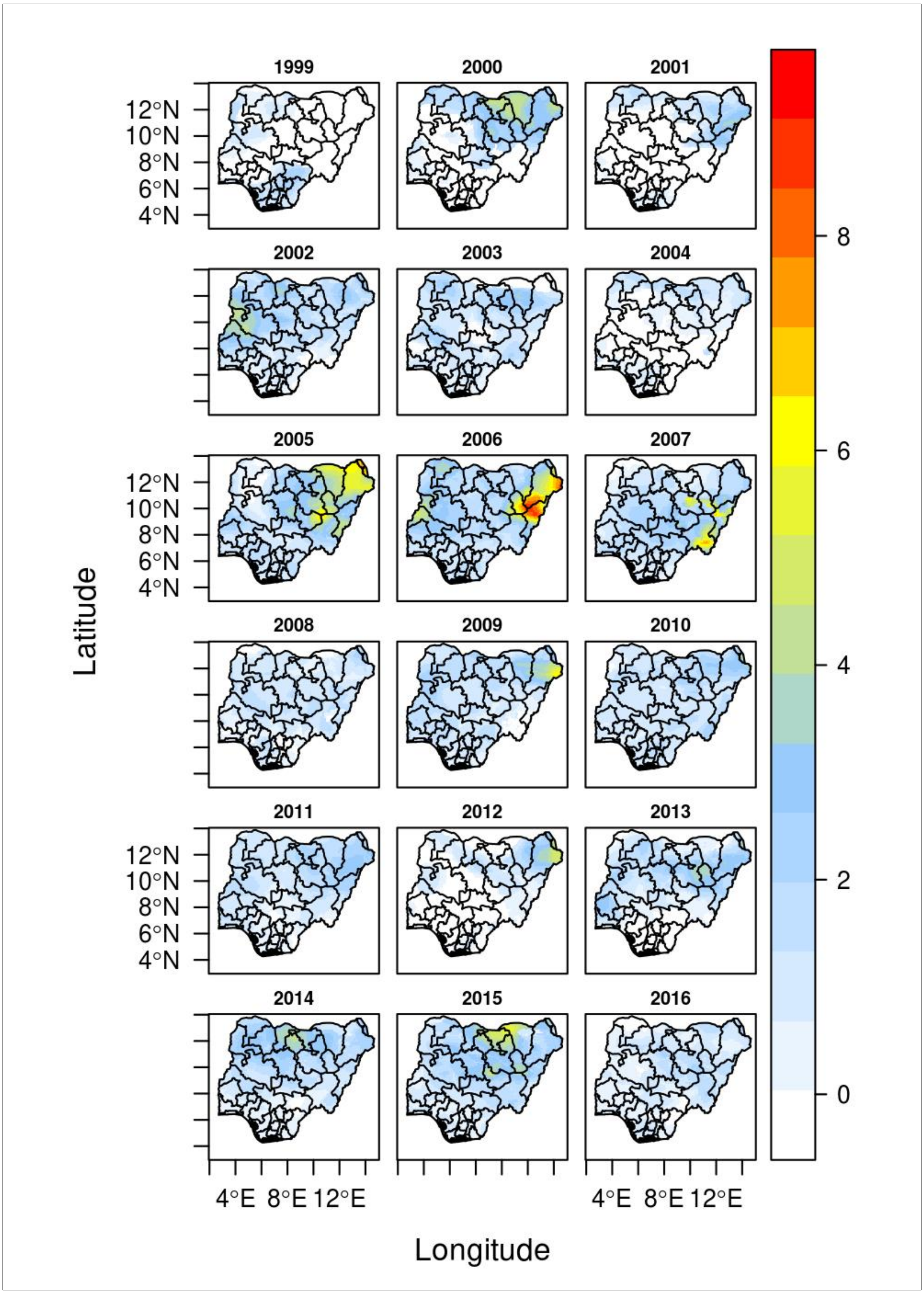

Figure 4.16b Heat Wave Amplitude (HWA) for EHF; 1999-2016

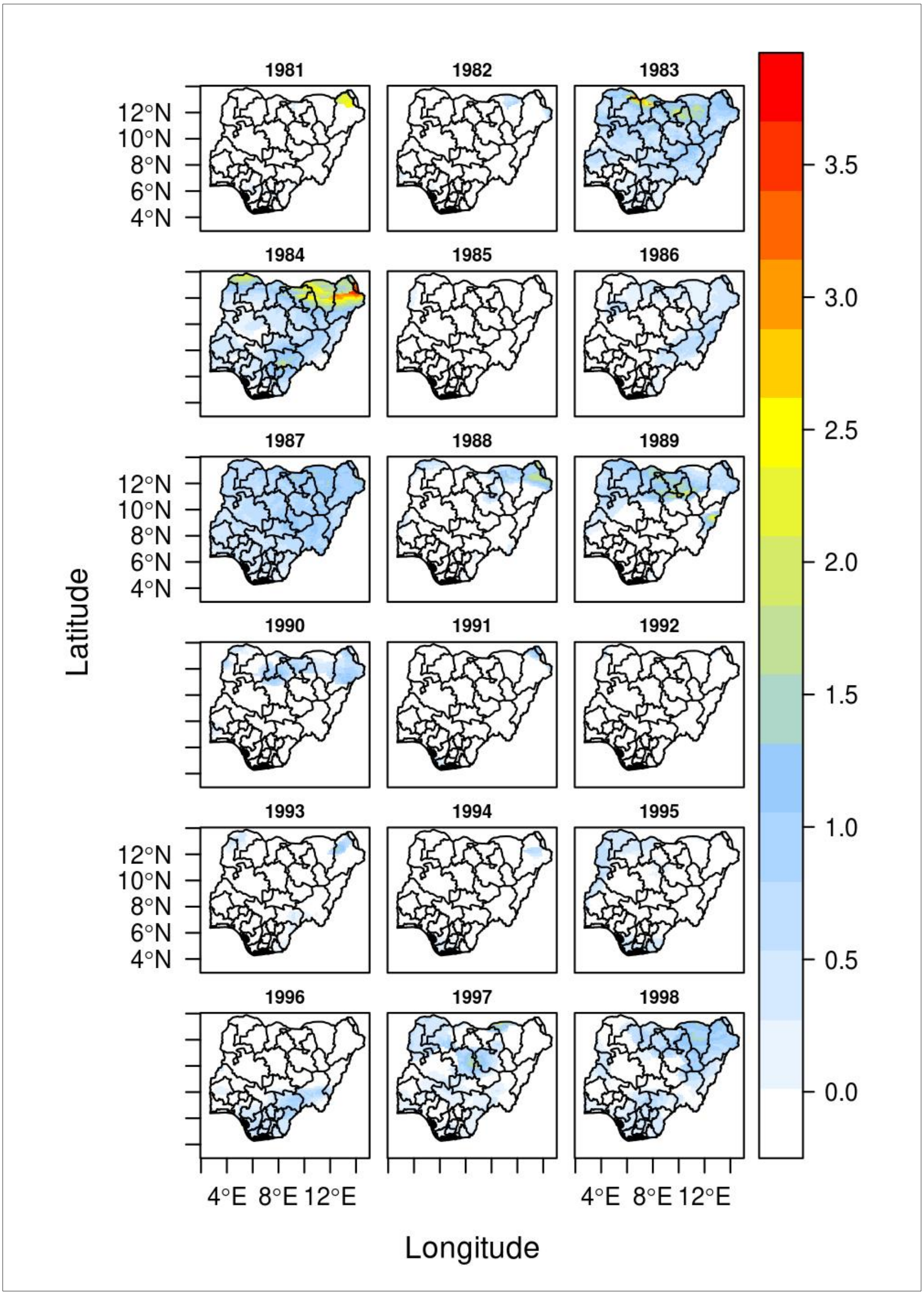

Figure 17a Heat Wave Magnitude (HWM) for EHF; 1981-1998

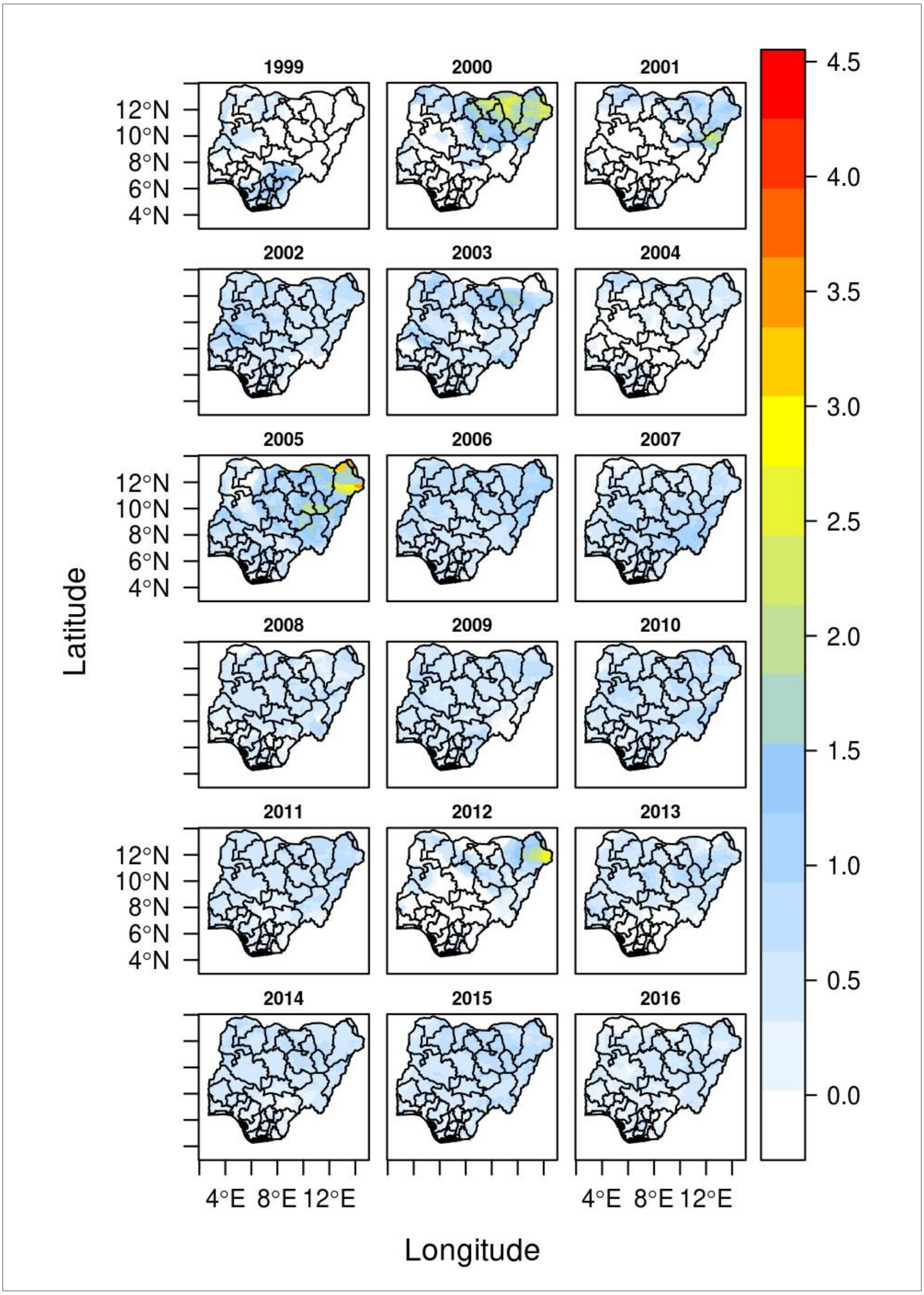

Figure 4.17b Heat Wave Magnitude (HWM) for EHF; 1999-2016

Heat waves have been classified into classes: ≤ 1 Normal < 2 ≤ Moderate < 3 ≤ Severe < 4 ≤ Extreme < 8 ≤ Very Extreme < 16 ≤ Super Extreme < 32 ≤ Ultra Extreme.

HWMId have been computed on TX and TN in this study. The HW occurrence had a different pattern with this index. The Figure 4.18a,b displays a general overview of HWMId in Nigeria from 1981-2016. The general magnitude of TX varies from 1 to 30, from Normal to Super Extreme. The years from 1981 to 1986 revealed an extreme HW (magnitude = 5) all over the country with a Super Extreme HW (magnitude = 17) in Cross River in the Coastal zone in 1983. Cross River in the South East also experienced a Super extreme HW of the magnitude of 25 in 1990 and Ebonyi, Enugu, Delta and Bayelsa followed with Super extreme HW. The Guinea and Sudan Savannah zones were more affected by HWs than the Sahel. Exceptionally, the period 2002-2010 had shown extreme (magnitude 5-8) HWs in the Sahel, compared with a more prevalent occurrence in the East of the country. The recent years 2011 to 2016 revealed magnitudes that peaked at 15 (very extreme) in the Southern States of Akwa-Ibom, Enugu, Ebonyi, Abia and Imo.

In Figure 4.19a,b the HWMId on TN is slightly different from the TX. The magnitude of HWs were lower and affected more the Coastal, Tropical Rainforest and the Savannah zones with super extreme HW events in 1998 affecting principally Kogi State, Nassarawa, Abuja FCT, Niger and Ondo States. The Sahel was less affected by severe HWs. In 2007, Niger State was particularly affected by a very Extreme HW. This is particular because only Niger State was affected by such an intense HW in 2007. In 2010 Ekiti was stricken by a Super extreme HW and Kwara, Osun, Oyo, Ondo, Edo, Kogi, Ebonyi and Enugu had a very extreme HW. In 2016, only the coastal zone was affected by a HW of magnitude of 15 (very extreme). The year 2016 has been declared as the hottest year (Schmidt and Arndt, 2017).

The present study using four definitions and comparing them has shown that HW occurred in Nigeria from 1981 to 2016 and almost every year. The occurred HWs have Number of Events, Duration, Frequency, Amplitude and Magnitude that are the characteristics/aspects of HW.

The three definitions, namely the TX90, TN90 and the EHF, showed in many cases the same pattern revealing a relationship in the definitions; especially TX90 and TN90 that depends respectively on TX and TN (maximum and minimum temperature). The results revealed also that the HWMId captures the magnitude and intensity of HWs without following the spatial trend of temperature in Nigeria.

These results follow the same occurrence of HWs in Balogun *et al.* (2016) for HW characteristics in Nigeria using the EHF definition. The different zones from the Coastal zone to the Sahel were considered in the study and they revealed the occurrence of HWs in mainly 1983, 1987, 1999 and 2005 and the major site of HWs was the upper zones especially the Sahel.

The results of the study follow the conclusion of (Ceccherini *et al.*, 2016a; Russo *et al.*, 2016). There is an increase of HWs in the last past 10 years. And this increase is liable to go on under climate change conditions. The occurred HWMId in 1990 of magnitude 32 (in the Tropical Rainforest) in Nigeria can be compared to all the HWs previous to the European Summer published in *the Guardian, 29 August 2003* that killed 11000 people and could also be compared to the European Summer. The European Summer highest HWMId was 24-36 (Russo *et al.*, 2015) while the highest peak of Nigerian $HWMId_{tx}$ was 32 in Ebonyi and Enugu (1990) and 20 in the coastal Eastern zone (2016). But none of them can be compared to the Russian 2010 HW published in *The New York Time, on July 19 2010*, that wilt their crops (Russo *et al.*, 2015).

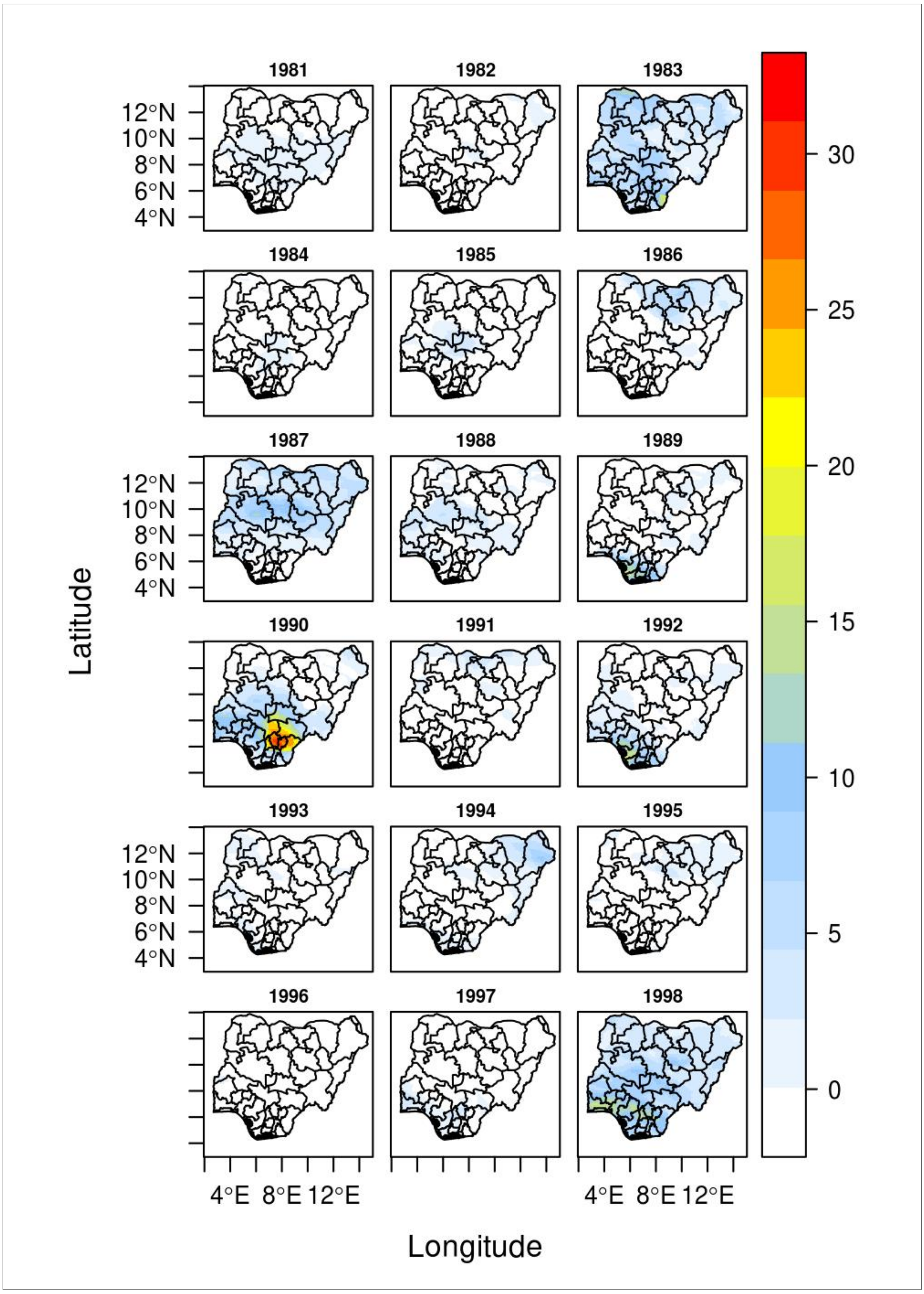

Figure 4.18a Heat Wave Magnitude Index daily ($HWMId_{tx}$) for maximum temperature (TX); 1981-1998

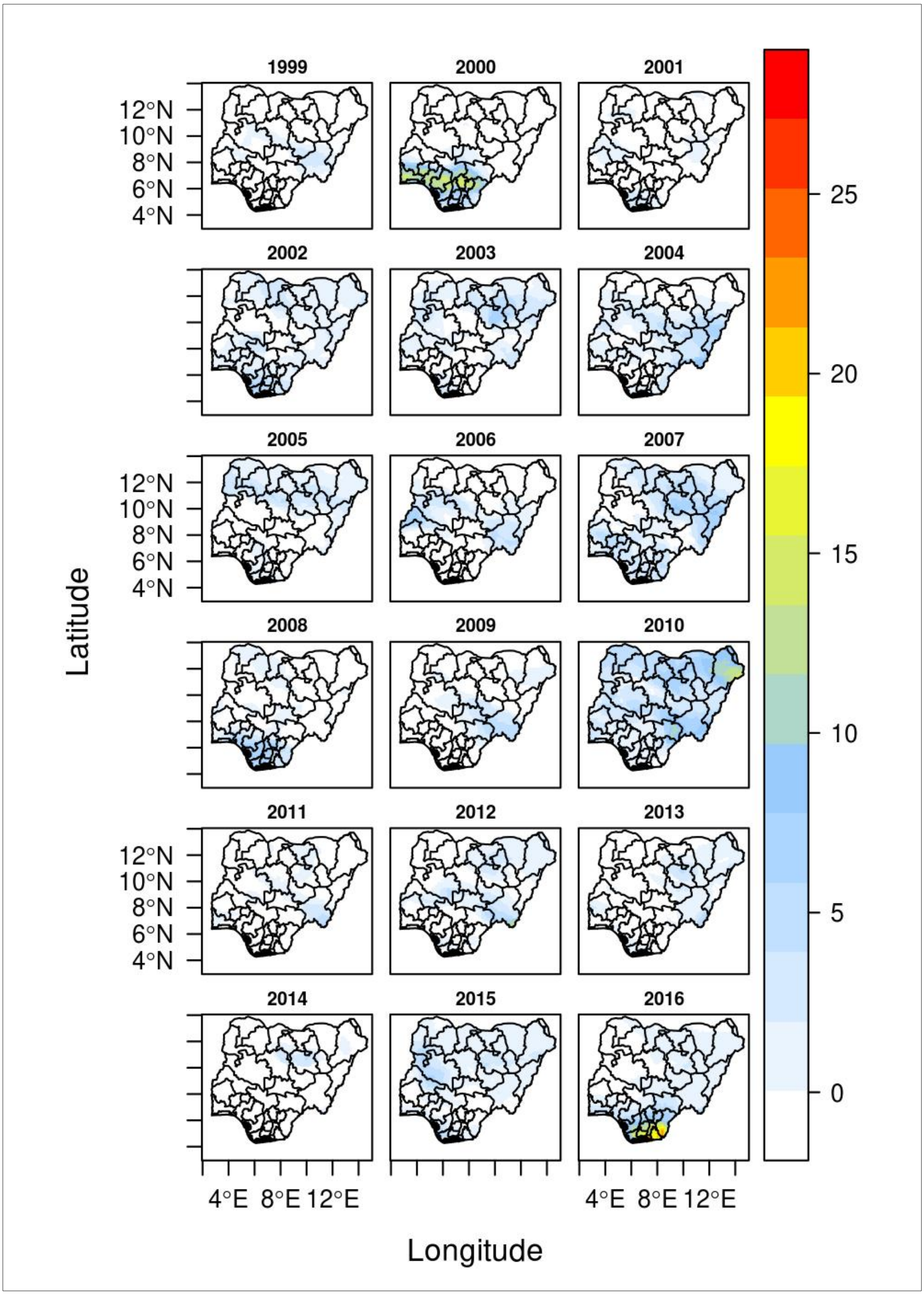

Figure 4.18b Heat Wave Magnitude Index daily ($HWMId_{tx}$) for maximum temperature (TX); 1999-2016

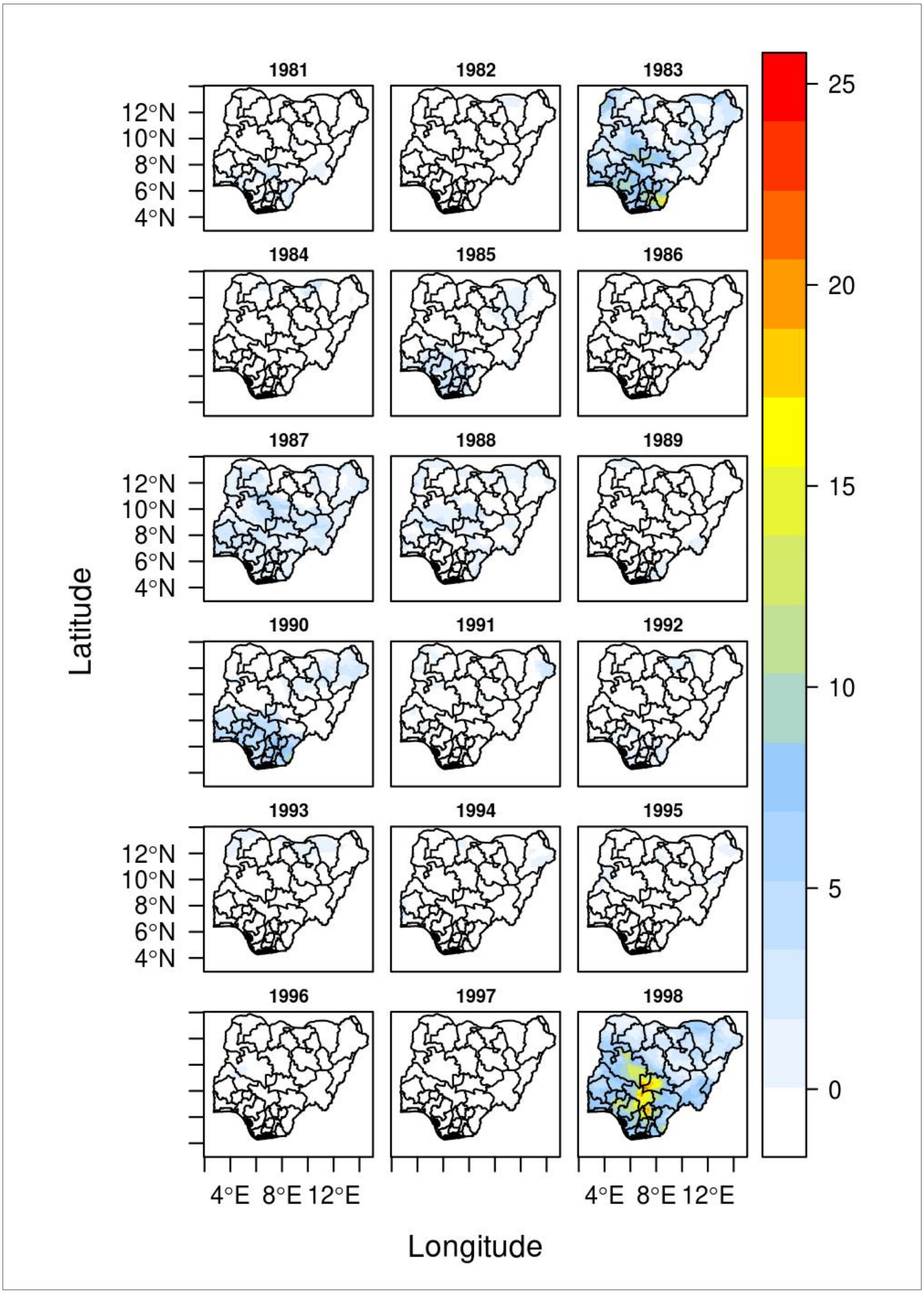

Figure 4.19a Heat Wave Magnitude Index daily ($HWMId_{tn}$) for minimum temperature (TN); 1981-1998

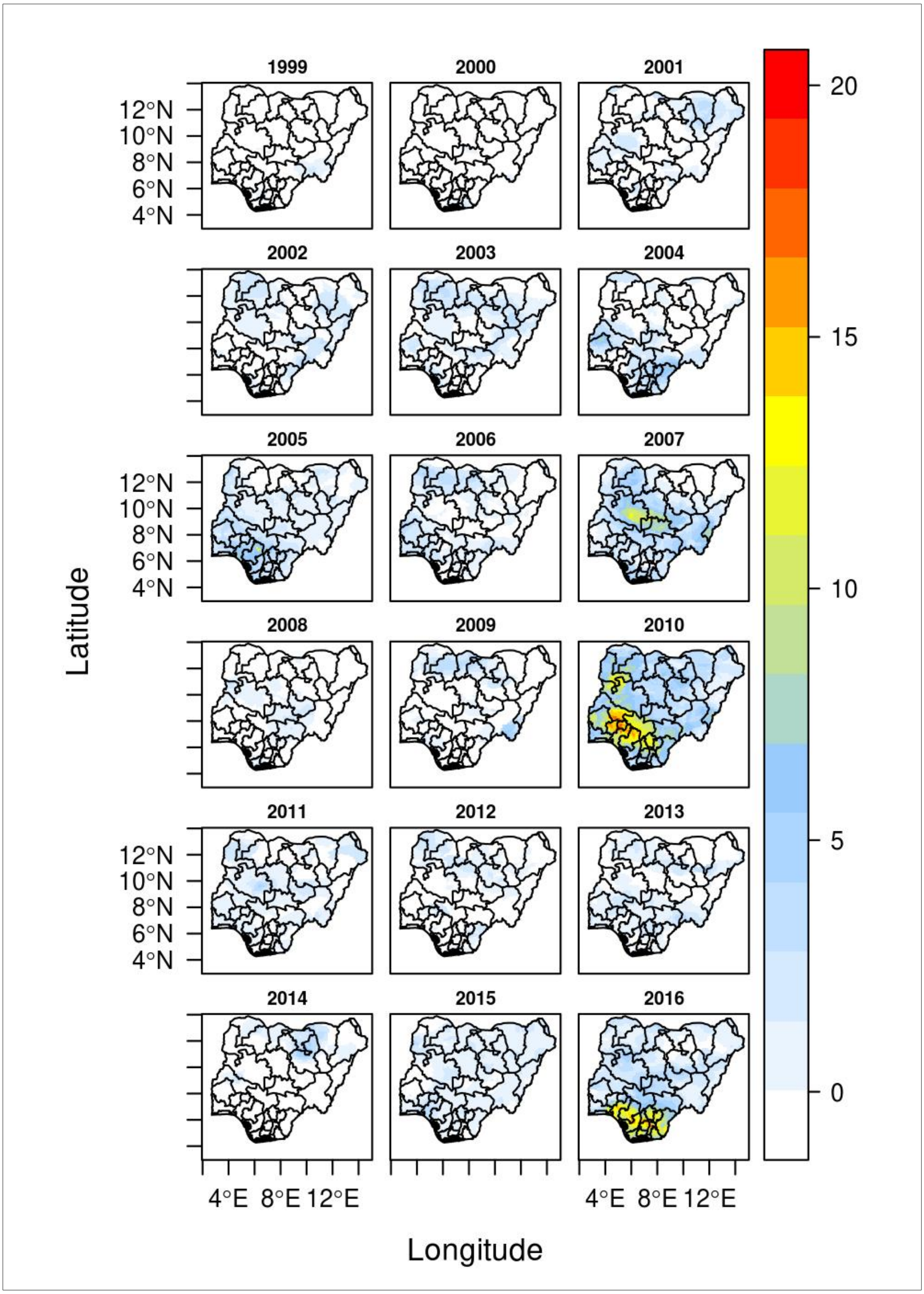

Figure 4.19b Heat Wave Magnitude Index daily ($HWMId_{tn}$) for minimum temperature (TN); 1999-2016

4.3 Prediction of Heat Wave (HW) Aspects/Characteristics to 2100

The prediction was carried on Weather Research and Forecast (WRF) outputs under the Representative Concentration Pathways (RCPs), RCP4.5 and RCP8.5. The temperature indices were presented, then the HW indices from 2018 to 2100.

4.3.1 The warmest days and warmest nights (TXx and TNx)

The hottest days (TXx) in Nigeria are spatially distributed according to temperature pattern. The Figure 4.20 shows the hottest days in average of 5 (five) years from 2018 to 2100. Under RCP4.5 the TXx will vary from 30 to 46 °C according to the zones from the Coastal zone. The Sahel will then record the highest TXx from 2018 to 2100 followed by the Sudan Savannah and the Guinea Savannah except for the Jos Plateau which always present a lower temperature because of the natural conditions (altitude). From 2063, the Western part of Borno State will be having TXx of 46 °C and this will expand to Yobe from 2093. The coastal zone will still have the lowest temperature even to 2100 but a slight increase is observed from 2093. The unspecific increment of temperature due to the change in actual climate is the reason of the increase of TXx.

The hottest days under RCP8.5 show the same pattern like RCP4.5. Indeed, in Figure 4.21, the 5 years average show more intense warmest days temperature (48 °C) from 2078 in the Sahel. The Coastal zone will be warmer in 2078 and the Jos Plateau will have a hotter temperature (37 °C). From 2088 in the Sahel, Borno State, Yobe, Adamawa in the East and Sokoto in the West will be having almost 50 °C of TXx and from 2093 Jigawa, Kebbi and Taraba will follow. The pessimistic scenario (RCP8.5) shows more intense TXx events compared to the realistic scenario (RCP4.5) previously analysed.

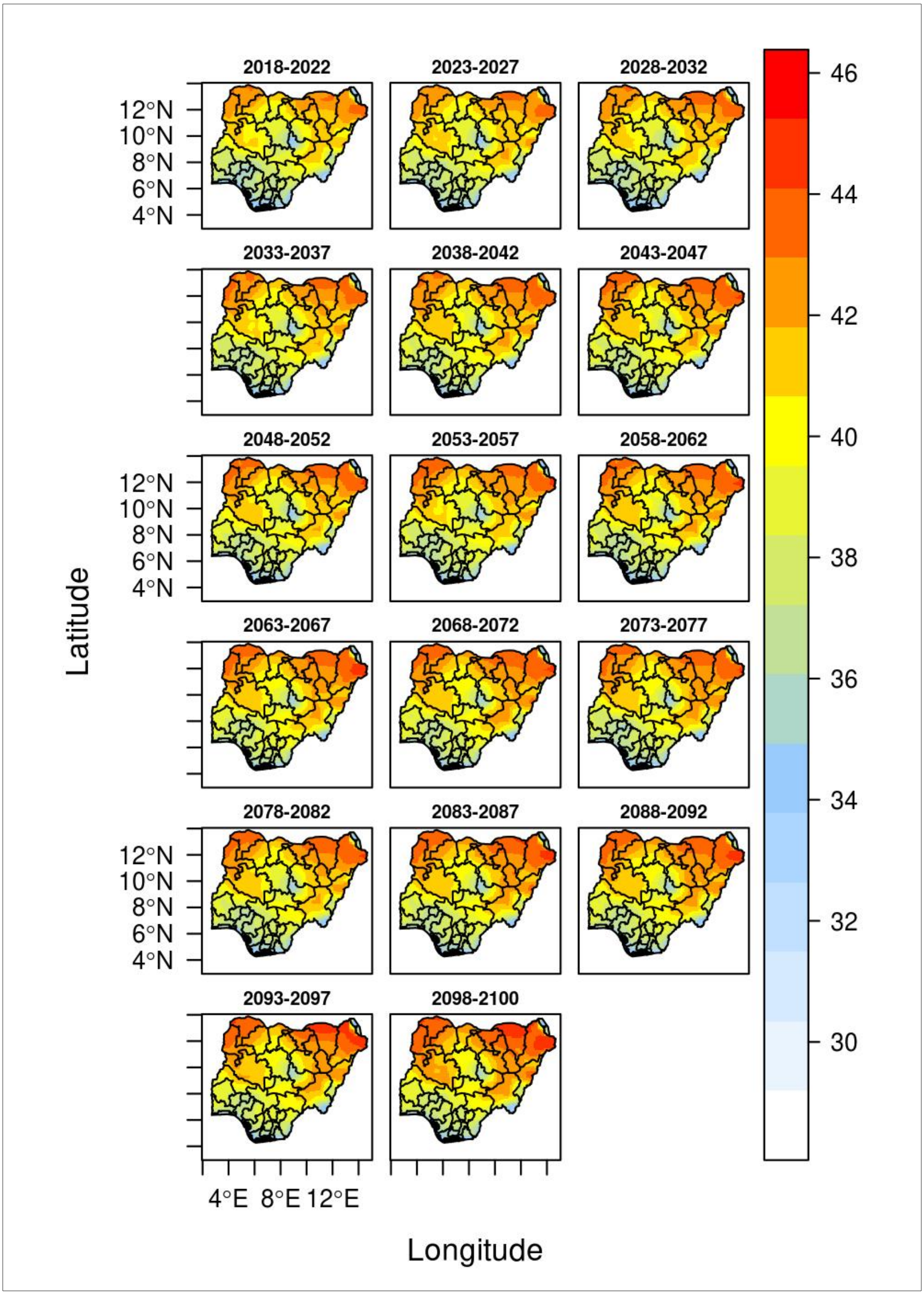

Figure 4.20 The Warmest Days (TXx) in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

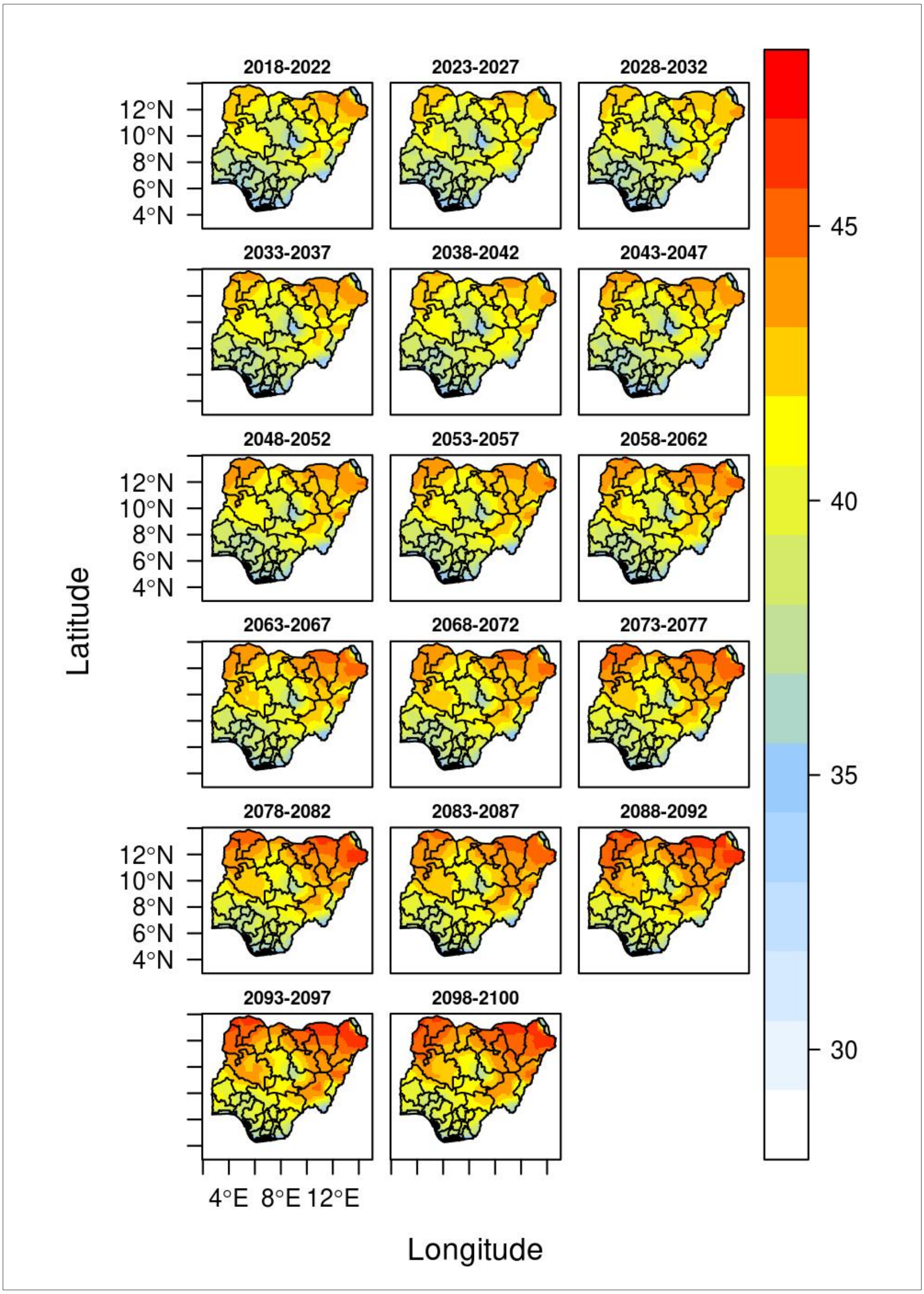

Figure 4.21 The Hottest Days (TXx) in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

The warmest nights will have the same pattern as the warmest days. Under the RCP4.5 in Figure 4.22, only the Sahel will experience 30 °C temperature as warmest nights especially in the extreme North West and North East. Some area in Borno State (Sahelian zone) will be having 33 °C like during the period 2048-2052. This will be frequently observed and will be increasing in space in the Sahel like in 2088-2092. The Jos Plateau in the Guinea Savannah will maintain the temperature within 22 °C and 25 °C. The Jos Plateau will be warming from 2048, bringing the temperature from 24 °C to 26 °C. The average temperature of the centre of the Sahel will vary between 27 °C and 29 °C. On the other hand, the lowest latitude zones, the Coastal and Tropical Rainforest, will slightly increase in temperature raising the TNx to 27 °C from 2063. Under RCP8.5, the pattern will also be maintained but the highest temperature will increase to 35 °C. This extreme will be reached from 2078 in the Sahelian zone covering the two extreme area, in Borno, Yobe, Sokoto and Kebbi. This is noticed in the panel 2078-2082 of the Figure 4.23. A low temperature will be maintained in Jos Plateau, in the South East of Taraba, in Ekiti, Osun and the Northern part of Ondo State. The coolest areas are located in the Guinea Savannah and the Tropical Rainforest.

The general overview on the predicted TNx in Nigeria from 2018-2100 shows an increase in the average temperature over the years and an increase in the spatial coverage of the highest values of TNx either under RCP4.5 or RCP8.5. Under RCP8.5 the situation is worse; the highest TNx will reach 35 °C that is already a very hot weather for the minimum temperature (TN). The TXx are also alarming under the extreme RCP (RCP8.5) where the hottest days will be reaching 50 °C in the Sahel with 44 °C in average in the Sudan and the Guinea Savannah.

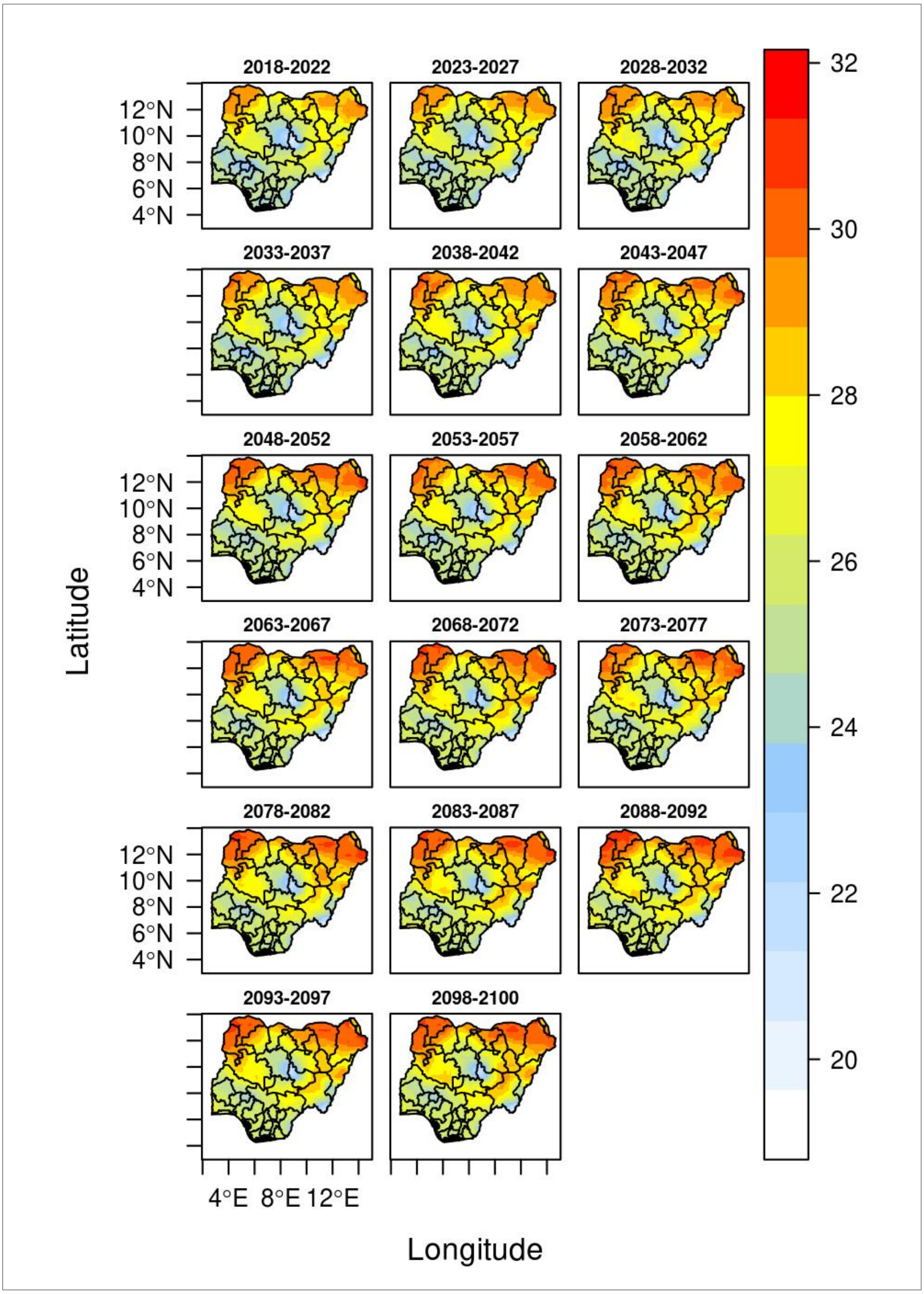

Figure 4.22 Hottest Nights (TNx) in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

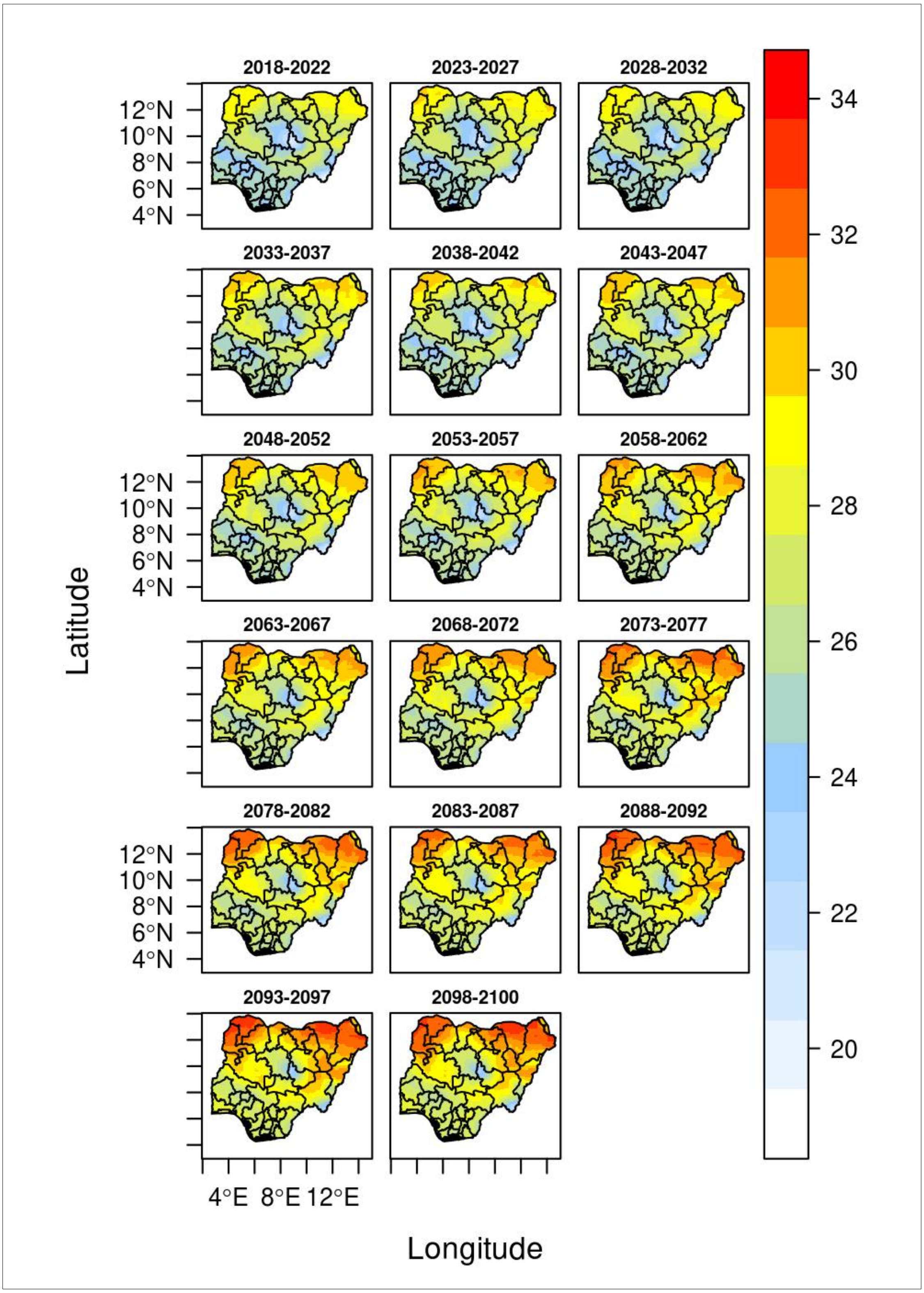

Figure 4.23 Warmest Nights (TNx) in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

4.3.2 Heat Wave Number (HWN) for TX90, TN90 and EHF

The HW number (HWN) of events in Nigeria has a different spatial pattern from the temperature (minimum and/or maximum) under RCP4.5. The Sudan Savannah and the Guinea Savannah will be affected by many more events in the future according to the observed pattern in Figure 4.24 with TX90. The number of events will be reaching 14 from 2040 and 17 during the period 2048-2052. During the same period of 2048-2052, Niger State will be affected by 17 HW events in average along with some part of Abuja (FCT), Plateau, Nassarawa and Bauchi States. The same number of HW will be maintained all over the period of prediction with some slight decrease in the aerial coverage of the high HWN. The Sahel will also be affected during that period but the HWN will vary between 8-10 and located especially in the Western Sahel. This time, the West of Nigeria will be spatially more affected than the East when considering HWN > 8. Niger State will be constantly affected by HWN > 10. The Coastal zone will almost be spared, with HWN < 2 events. The Tropical Rainforest will also be having in average HWN < 5.

The same pattern is observed under RCP8.5 where the periods 2043-2047 and 2063-2067 show the highest HWN and spatial coverage together in Figure 4.25. During the period 2063-2067, the HWN will be 17 in Niger, Kebbi, Sokoto, Zamfara, Kaduna, Bauchi, Plateau, Nassarawa, Gombe, Adamawa and Taraba States. The slight difference in the RCP8.5 is that, from 2058 all the Sahel, the Sudan Savannah and great part of Guinea Savannah will be covered by HWN > 10, and this is from East to West. The Tropical Rainforest will be totally covered by 5 HW events when the Coastal will be having 1 or 0 HWN from 2053. Before that, the Coastal will have 4 HWN/year.

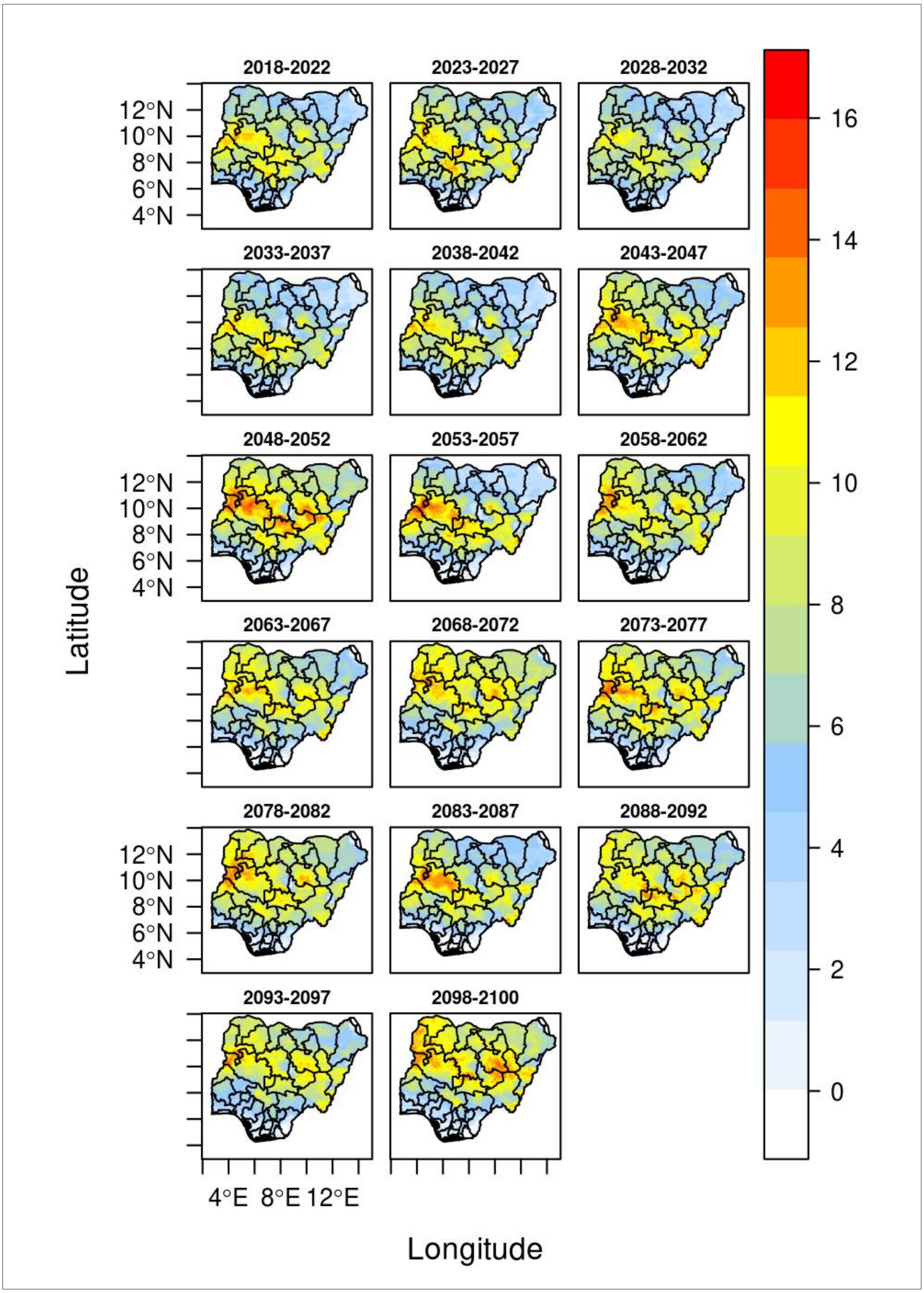

Figure 4.24 Heat Wave Number (HWN) using the 90th percentile of maximum temperature (TX90) in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

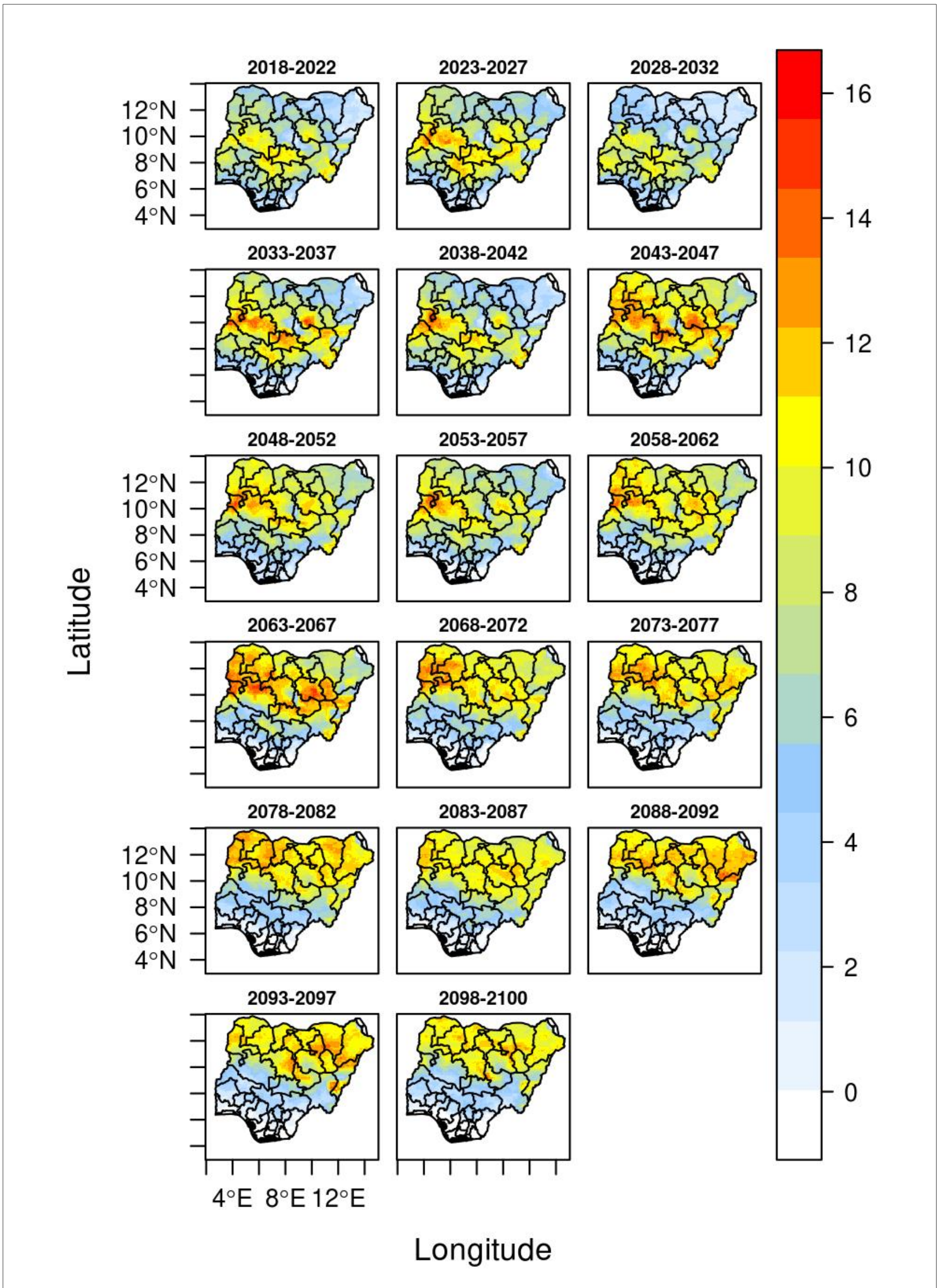

Figure 4.25 Heat Wave Number (HWN) using the 90th percentile of maximum temperature (TX90) in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

The HWN using the 90th percentile of minimum temperature (TN90) under WRF RCP4.5 outputs show in Figure 4.26 a different pattern from TX90. An overview on the results revealed the peak of HWN at 13 events. The pattern shows 8-11 events in the Coastal zone from 2018-2047. Then the aerial coverage will start increasing from 2048 occupying the Tropical Rainforest zone and the Guinea Savannah. The Sahel will be recording the lowest values (2-5) of events throughout the period (2018-2100). The HWN will increase spatially and also in number of events from 2083. The phenomenon will increase in space and cover almost all the Nigeria during the last period 2098-2100. The most affected State by the highest number of events in the Coastal and Tropical zone is Cross River State. In the Guinea Savannah, Taraba, Adamawa, Niger, Nassarawa and Benue States were also affected by important number of events. Niger State will be the Location of many HW events during the period 2098-2100.

In Figure 4.27, the Coastal zone shows an average of 9 events from 2018-2042 under RCP8.5. From 2043, the Tropical Rainforest and the Guinea Savannah will be all covered (9-12 events). From 2058 the HWN will increase and peak in Niger State at 12 events. From 2068, Niger State, Kebbi, Zamfara and Sokoto States will have between 14 and 15 events/year and the Sahel will be experiencing more HWN than the other zones.

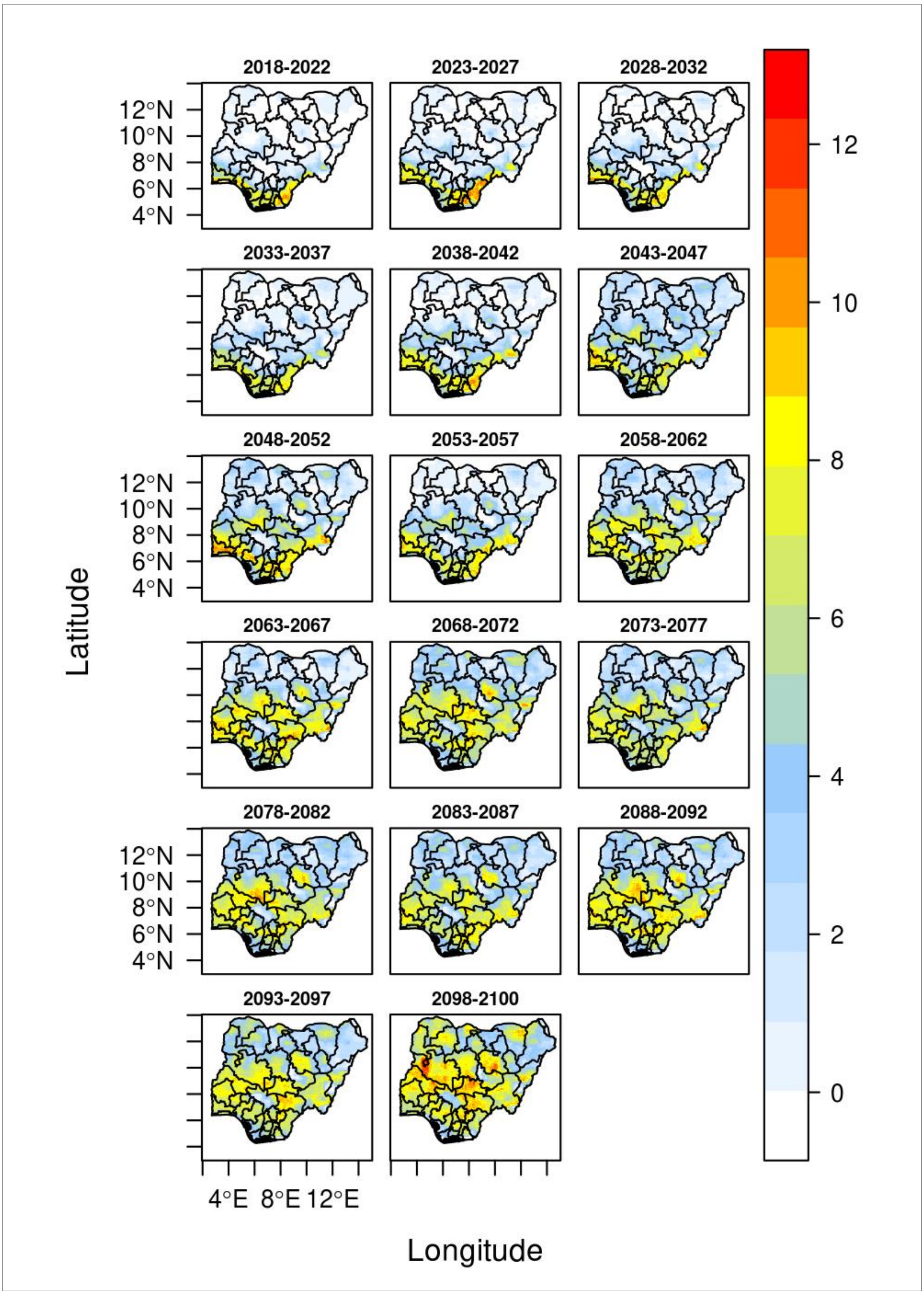

Figure 4.26 Heat Wave Number (HWN) using the 90th percentile of minimum temperature (TN90) in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

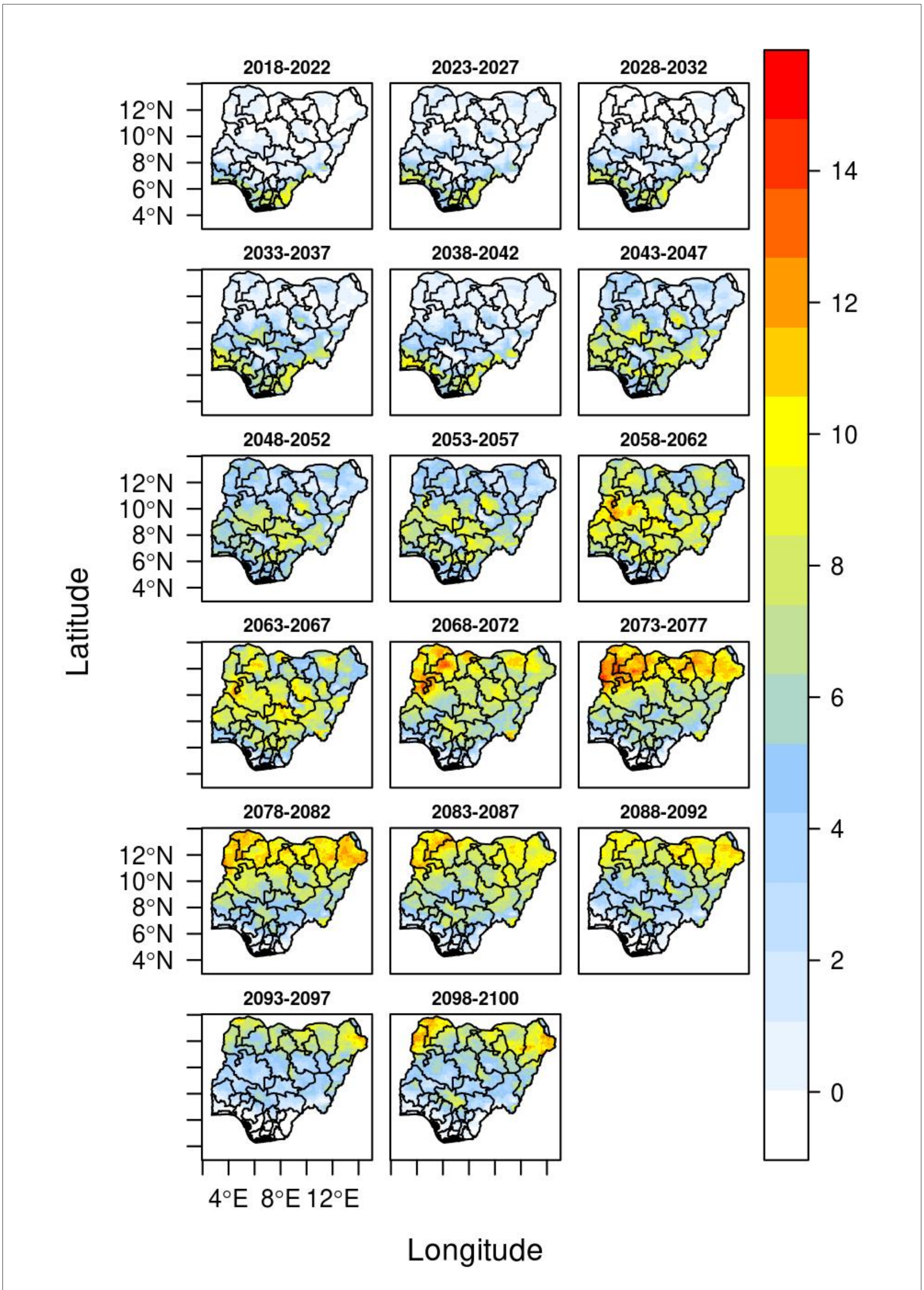

Figure 4.27 Heat Wave Number (HWN) using the 90th percentile of minimum temperature (TN90) in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

The HWN using Excess Heat Factor (EHF) under RCP4.5 as shown in Figure 4.28 has twelve (12) days as the peak of number of events. From 2018-2047 HWN will vary from 9 to 11 events/year. Like in HWN using TN90, the Guinea Savannah will be spatially the major zone affected by HWN. From 2048, Niger State will be the hotspot of HWs in number of events per year. The coverage will move mainly to the North West and this will gradually spread to the Northern part from 2063. The HWN will reduce with the EHF in average, and the Coastal zone will have no records of HWN. The prediction under RCP8.5 (Figure 4.29) shows also the Guinea Savannah as the most affected zone from 2018 to 2042. From 2048, the Sahel will have 10 to 12 HW events per year. The period 2048-2052 will record the highest HWN, 12 in the Northern part of Niger State and the South of Kaduna. The effect will be felt the most in the Sahel, Sudan Savannah and Guinea Savannah. The EHF reveals a HWN = 0 in the Coastal zone under RCP8.5.

There will be an increase in the aerial coverage of HWN in Nigeria. This is due to the increase in the mean temperature as the EHF is computed using the excess heat indices (EHI) based on the 90th percentile of TM (average temperature). The mean temperature will increase in many places in the Guinea Savannah and Sahel that will lead to the aerial extension and increase in the number of HW in the zones. The EHF is a good indicator of Mortality and morbidity (Hatvani-Kovacs *et al.*, 2016; Langlois *et al.*, 2013; Scalley *et al.*, 2015). The greater the index, the higher the exposure to mortality. The study of this index indicates an increase in the heat-related number of mortality and morbidity in the future in Nigeria, considering the increase in the aerial coverage of the affected zones.

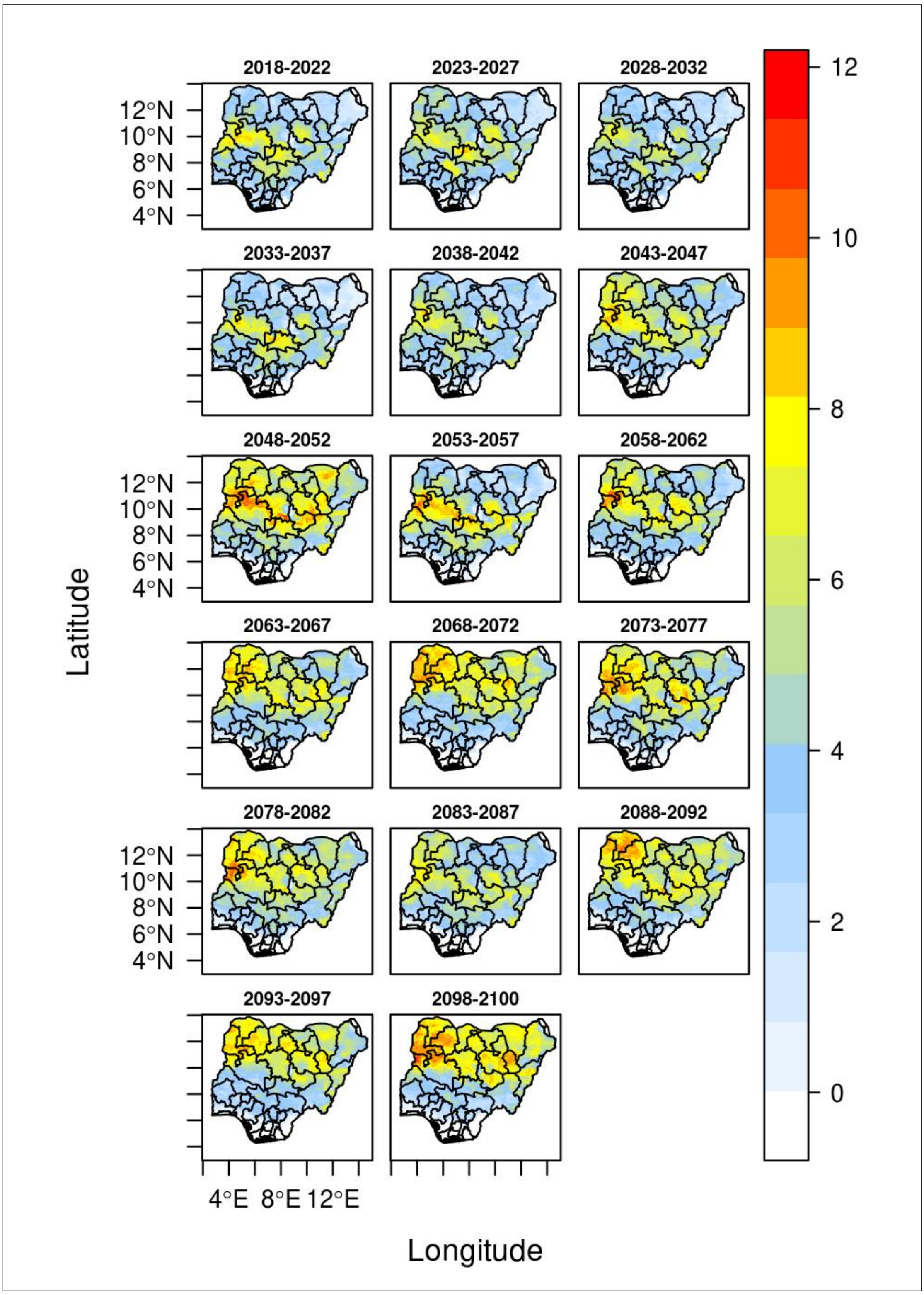

Figure 4.28 Heat Wave Number (HWN) using EHF in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

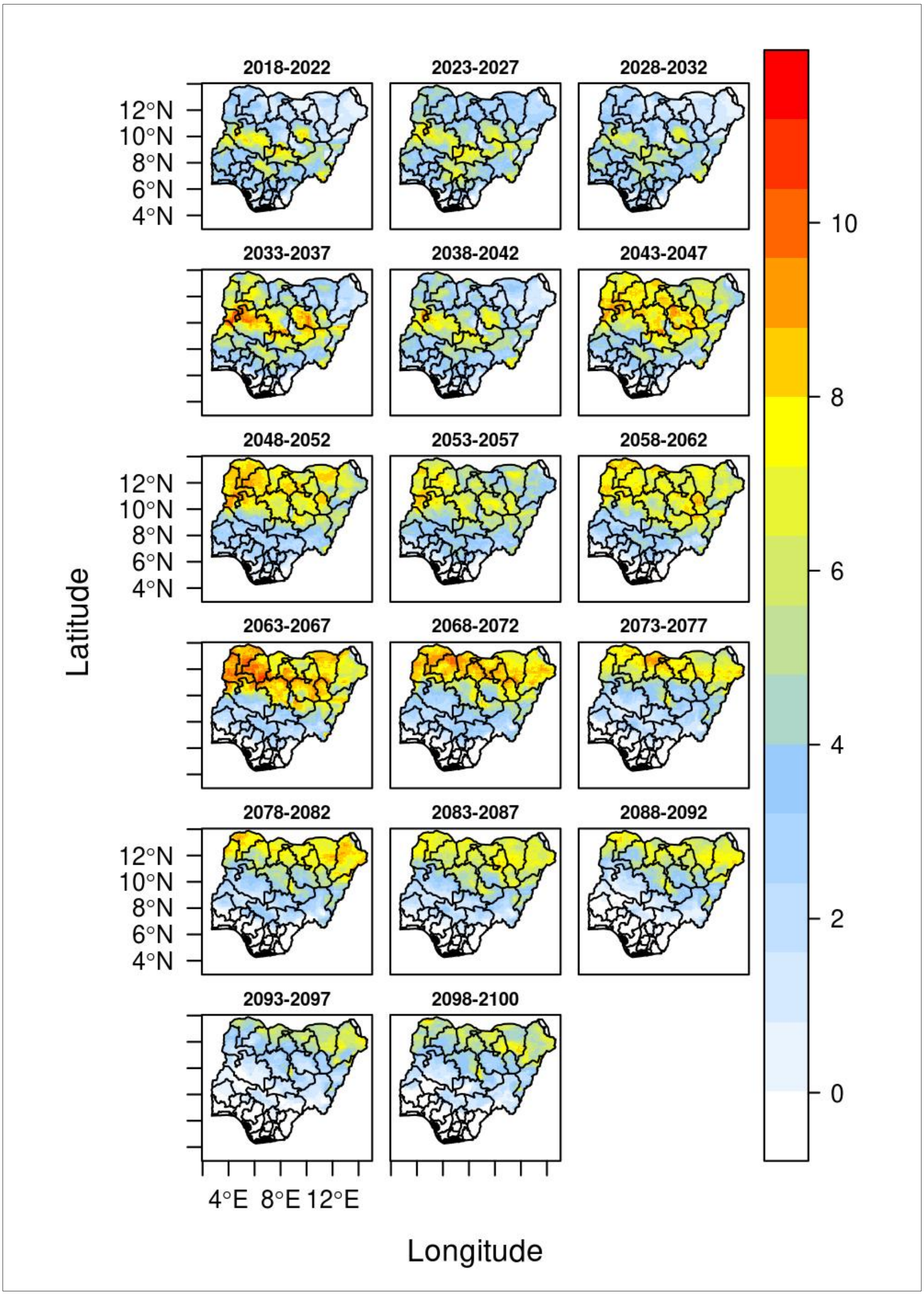

Figure 4.29 Heat Wave Number (HWN) using EHF in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

4.3.3 Heat Wave Duration (HWD) for TX90, TN90 and EHF

The duration (in days) of the longest HW using the 90th percentile of maximum temperature (TX90) under RCP4.5 show high number of days in the Coastal zone from 2018-2100. The longest HW in Nigeria will be 170 days during the period 2068-2072, 2073-2077 and 2083-2087 in the Coastal zone of Nigeria. This will affect mainly Delta, Bayelsa, Rivers, Akwa Ibom and Cross River States. The other parts like Lagos, Ondo, Ogun, Osun to Ebonyi and Enugu States will have 100 to 120 days of HW. The Tropical Rainforest will also be affected by 100 days of HW as the longest one while the Guinea Savannah that is the biggest zone will experience 40 to 60 days in average. The Sudan Savannah and the Sahel will experience 20 to 40 days under RCP4.5 using TX90 HW definition. The Figure 4.30 shows all the HWN for TX90. The realistic scenario (RCP4.5) is not very different from the extreme one (RCP8.5).

The Figure 4.31 that presents the results of HWN for TX90 under RCP8.5, has an identical pattern as the realistic scenario. The Coastal zone will be more affected than any other zone with 170 days of HW in the extreme South East. This is observed over all the predicted period, with the Sahel recording less than 50 days. But from 2063-2067 the Eastern part of the Coastal zone will have no record of HWD, while the Tropical Rainforest will record 160-170 days. The Guinea Savannah at the same time will be having 100-120 days. The shifting from Coastal zone to Tropical Rainforest will affect all the country moving the duration of HWs to the Sahel where the number of days of the longest HW will be around 60. From 2088 to 2100 there will be a constant move of HWD from the Coastal recording 0 to the Sahel where the number will be increasing.

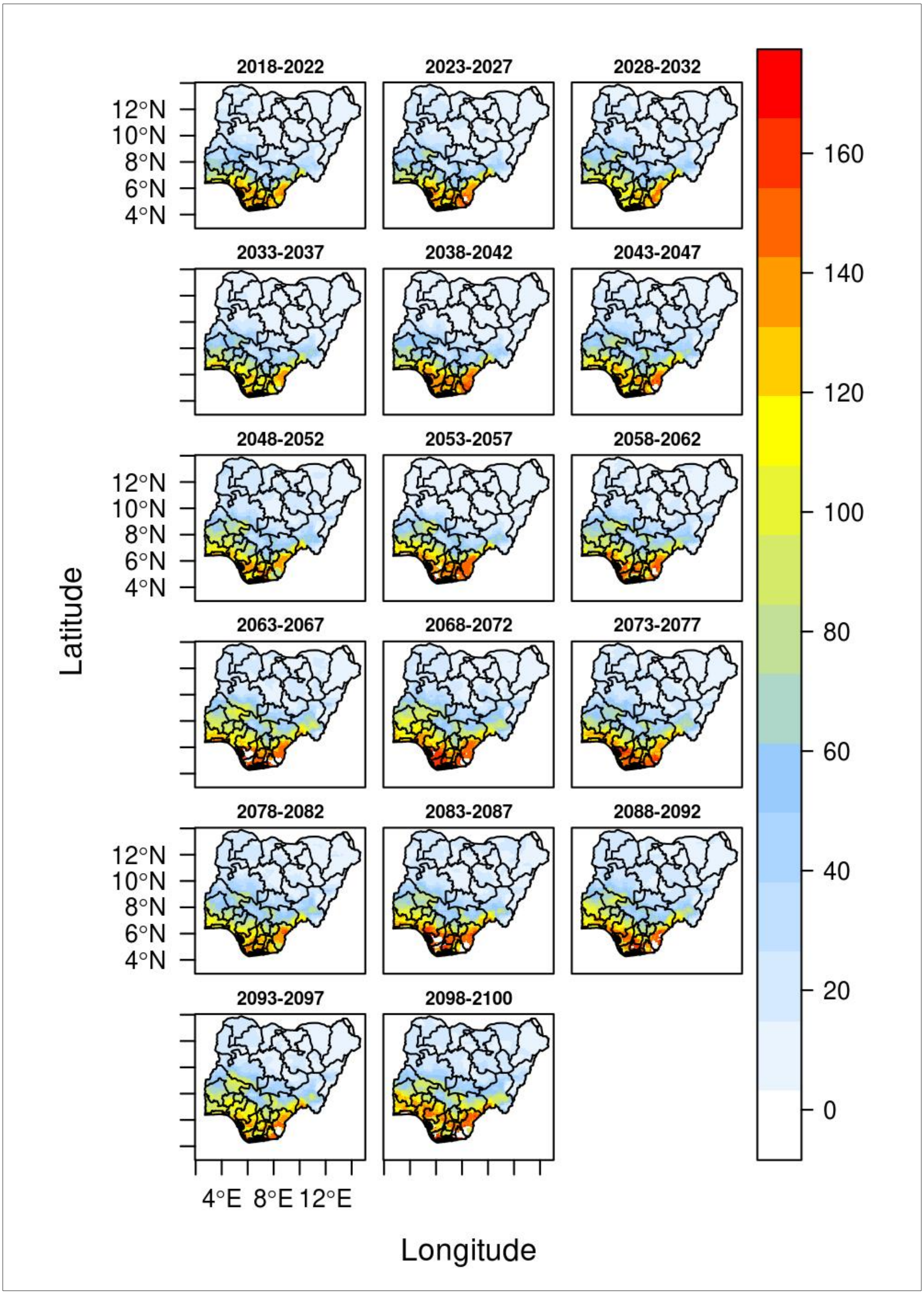

Figure 4.30 Heat Wave Duration (HWD) using TX90 in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

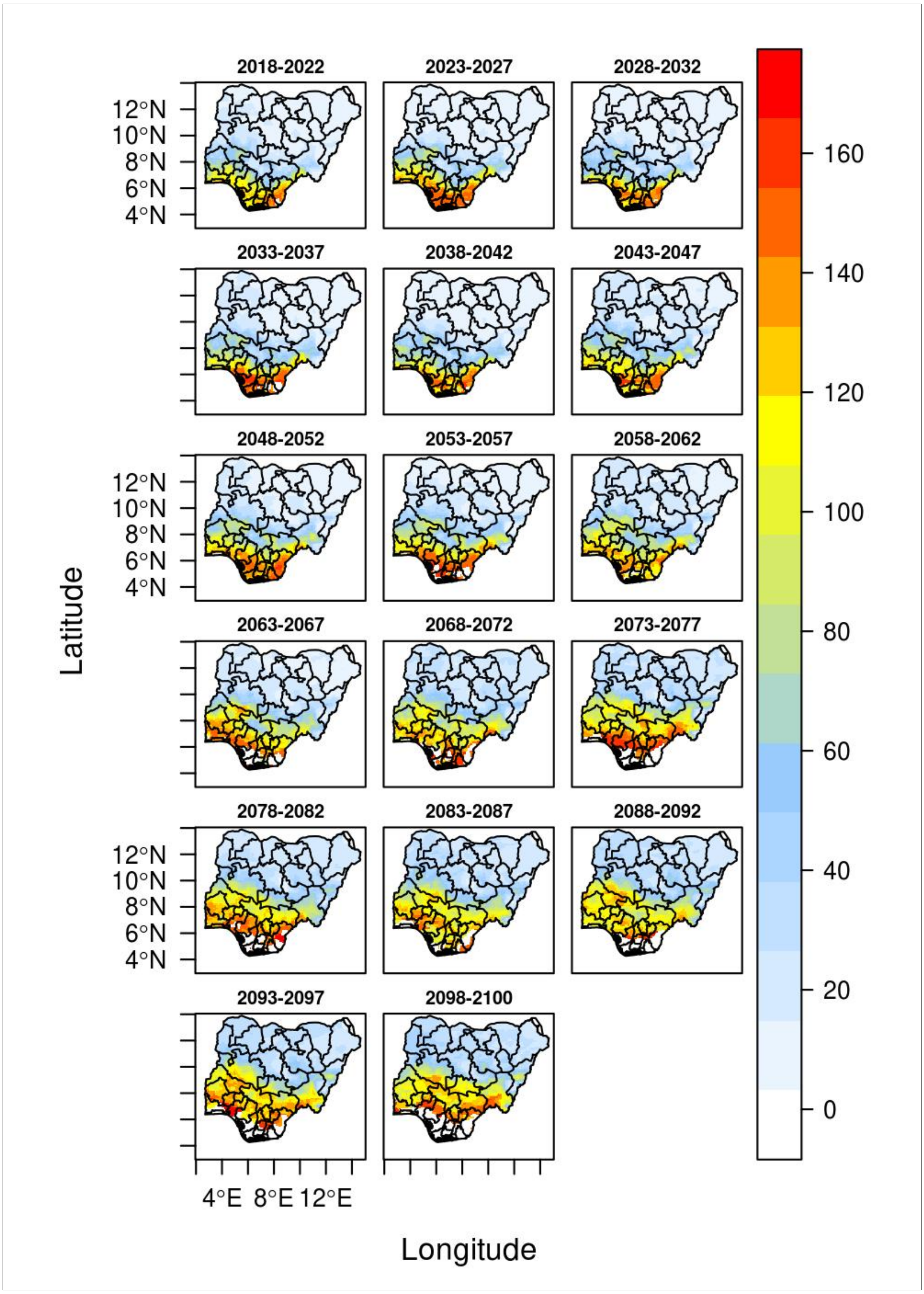

Figure 4.31 Heat Wave Duration (HWD) using TX90 in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

HWD with TN90 will have fewer days in average over the whole country and through the considered period under RCP4.5. The longest HWD with TN90 is the same as with TX90 under the realistic scenario (170), but the peak will be reached only after a long period, in 2098-2100. The Figure 4.32 shows from 2018 to 2042 an average HWD of 0-100 days with a lessening of days from the Coastal zone to the Sahel. From 2043, an increase in number of days of the longest HW in the South (Coastal and Tropical Rainforest) will be noticed. There will be a insistent increase till 2100 when the peak will be reached.

Under RCP8.5, the pattern is the same, see Figure 4.33. During the period 2018-2042, the average number of days in the country will be less than 100. But from 2043 the Coastal zone will see its number of longest HW days increasing to 140. The aerial coverage will also be increasing from the Coastal and Tropical Rainforest zones to the Guinea Savannah. During the last periods (2078-2100) of the predicted period, the Sudan Savannah will have 140 to 170 days especially in Ogun, Oyo and Lagos in the West and Taraba, Benue and Cross River in the East. Kwara, Niger and Bauchi States will also be affected.

HWN will be high especially in the Southern part of the country either under RCP4.5 or under RCP8.5. The number of HW days in terms of duration will be increasing from the Coastal zone to the Sudan Savannah from 2058 under the two scenarios.

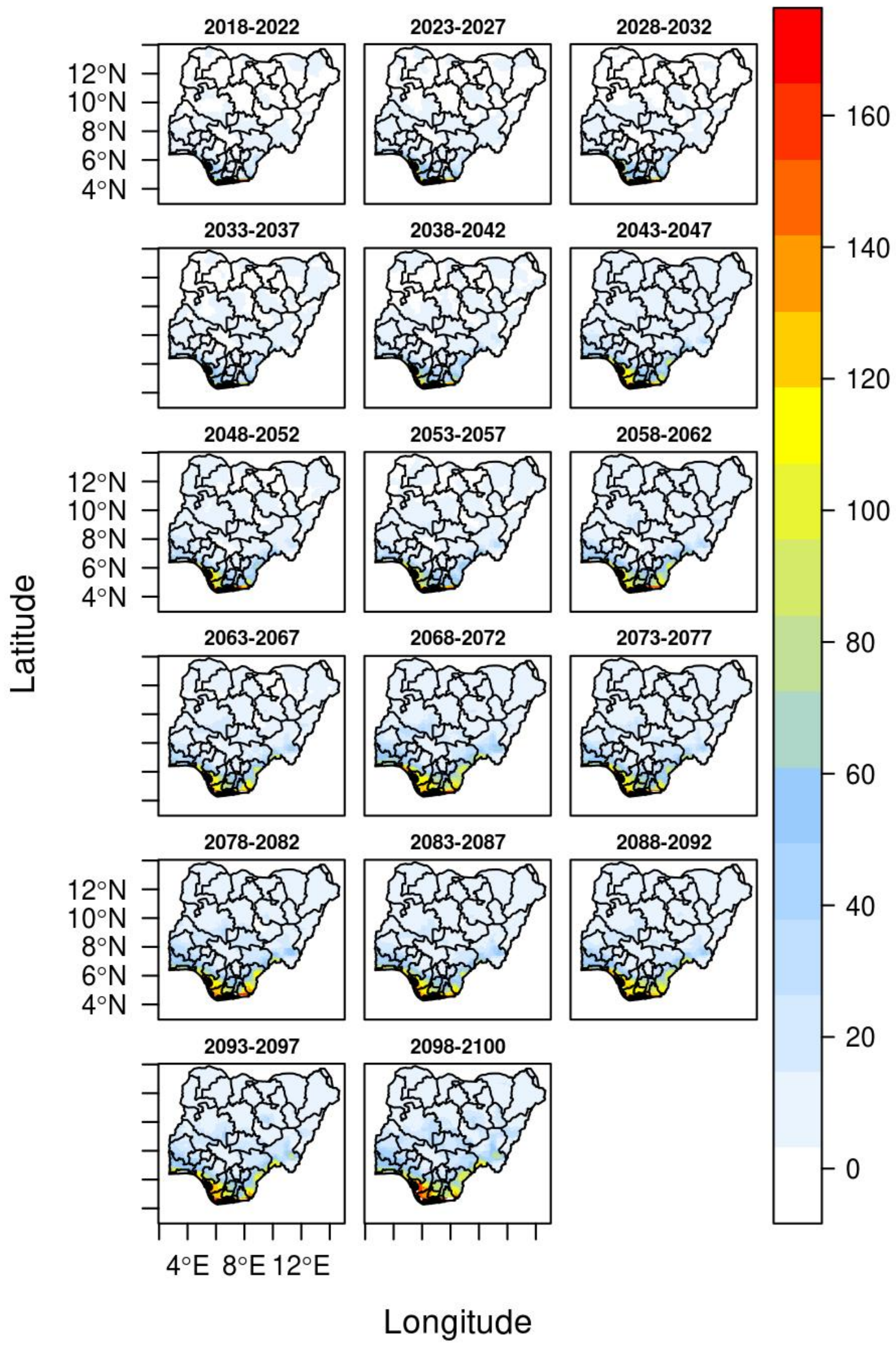

Figure 4.32 Heat Wave Duration (HWD) using TN90 in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

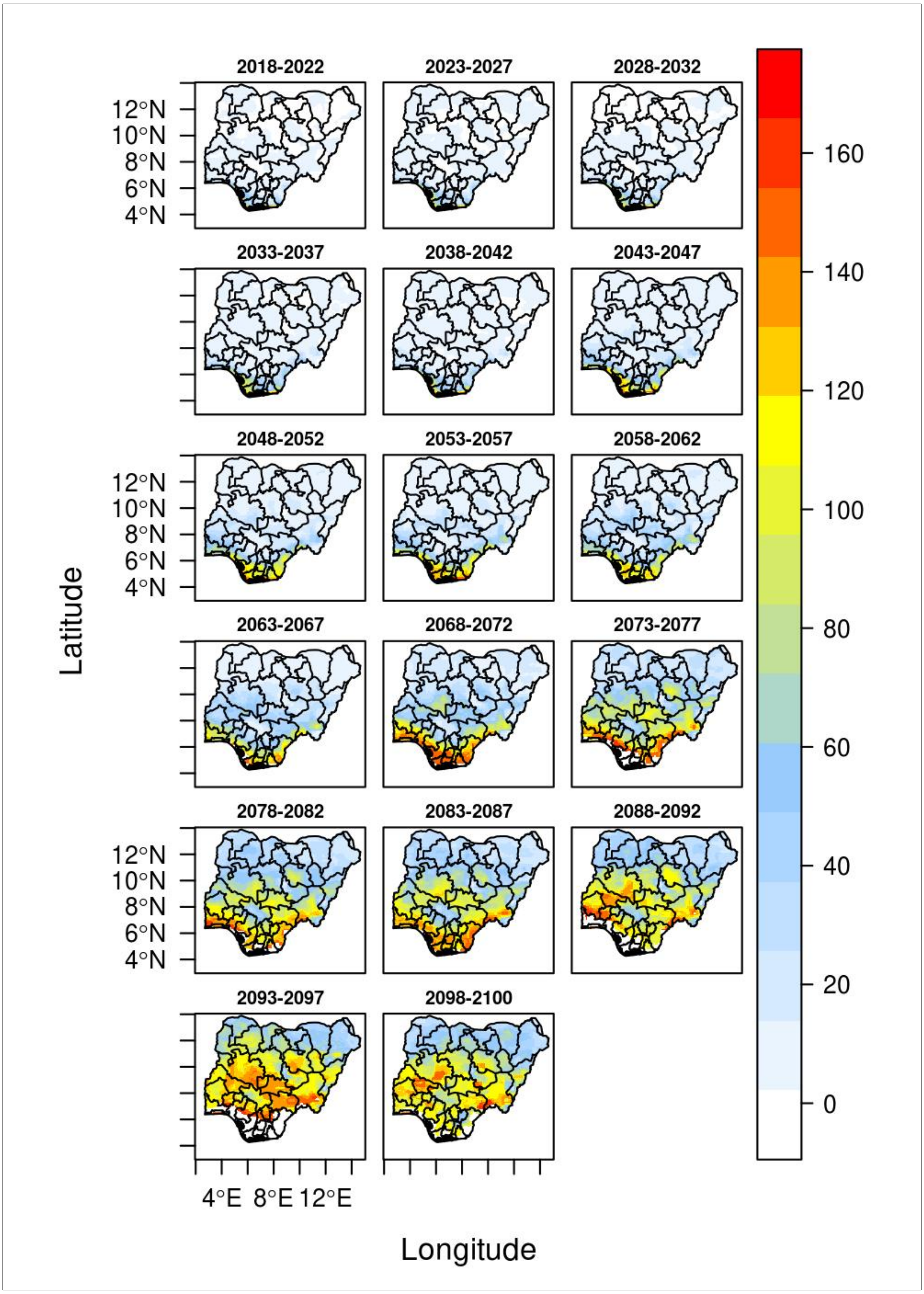

Figure 4.33 Heat Wave Duration (HWD) using TN90 in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

Under RCP4.5, the EHF shows the same pattern as with TN90 affecting mainly the Coastal zone with 150 days of HWD in Figure 4.34. But in this definition, the Tropical Rainforest is also affected with 120 days of HWD. From 2033 the East of Coastal zone will record 0 day leaving the Tropical Rainforest with 150 to 160 days. The Guinea Savannah will be affected by 60 to 120 days and the Sahel and Sudan Savannah will record 20 to 40 days all through the years.

Under RCP8.5 the pattern will stay the same in Figure 4.35. The number of days will be higher under this last scenario than in the RCP4.5. From 2018 the Coastal zone will experience more HWD for some years because, from 2033 to 2100 except for the period 2038-2042, the Coastal zone will experience 0 HWD. The Guinea Savannah will be greatly affected by very long HWs of 100-170 days. Taraba, Niger, Kogi, Abuja (FCT), Kwara and Oyo States will be having 160-170 days. Even some area of the Tropical Rainforest will have 0 as HWD from 2073-2077. The Sudan Savannah will experience 60-110 days of HWD close to 2100.

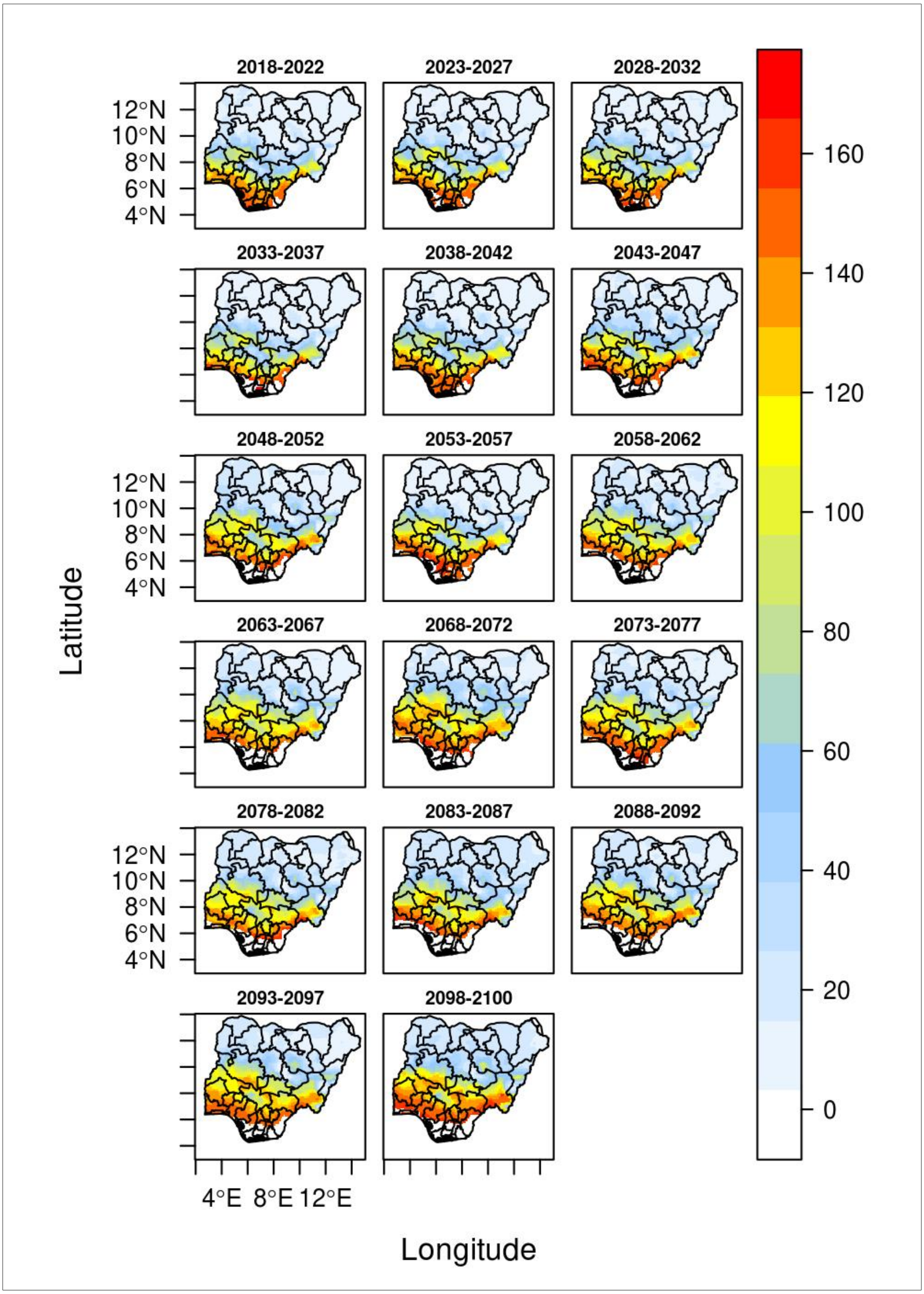

Figure 4.34 Heat Wave Duration (HWD) using EHF in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

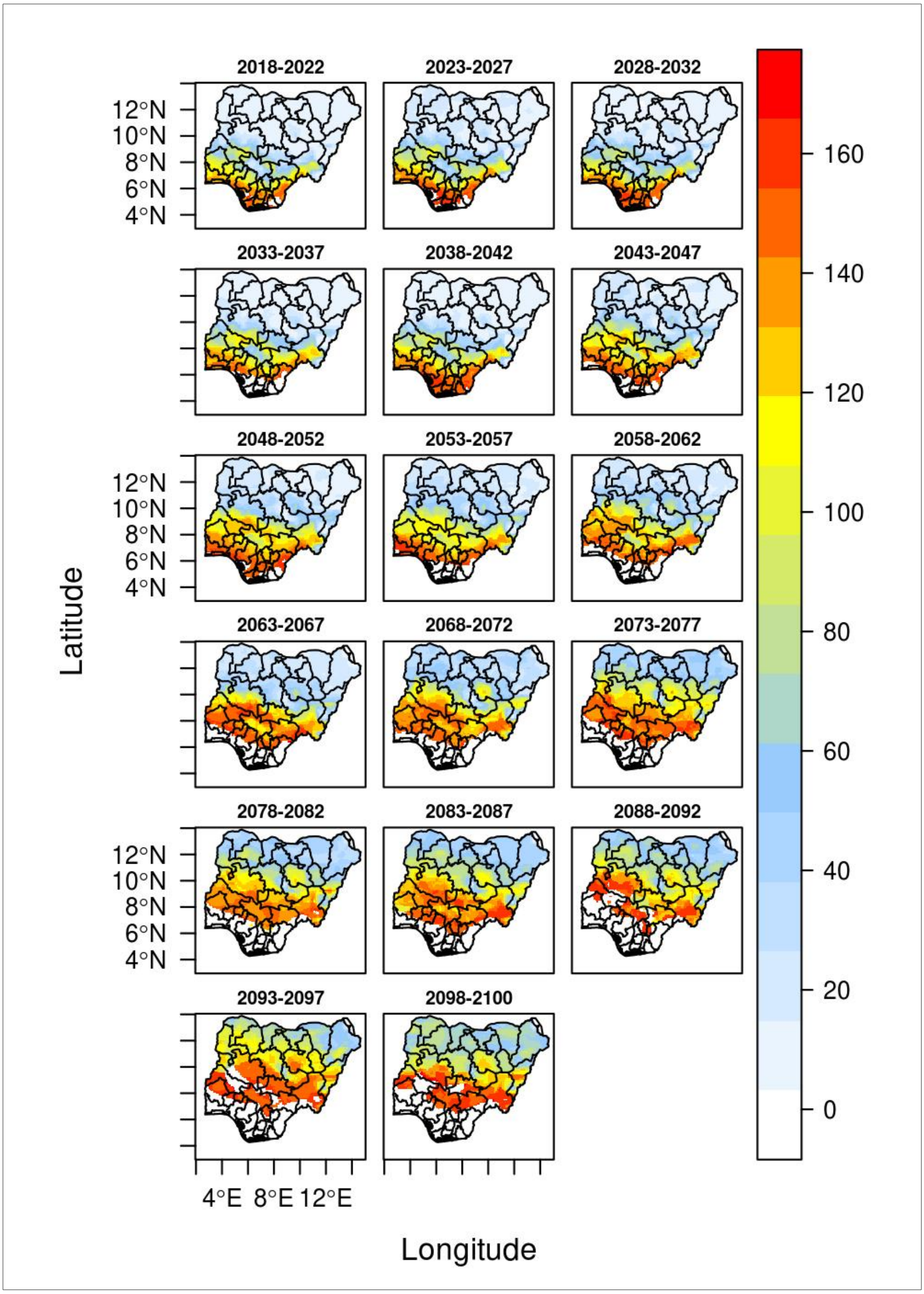

Figure 4.35 Heat Wave Duration (HWD) using EHF in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

4.3.4 Heat Wave Frequency (HWF) for TX90, TN90 and EHF

The HWF under RCP4.5 in Figure 4.36 shows 170 days that contributed to individual HWs in the Coastal zone. 170 days is the highest frequency for the future HWF under the realistic scenario from 2018 to 2100. From 2048 the extreme South of the Coastal zone will have a frequency of 60 days while the Guinea Savannah will be between 120 and 140 days. From 2043 the extreme South Eastern part of the Coastal zone will experience HWF of 50 days and this for the rest of the years. At the same time, the Guinea Savannah will be experiencing HWs of 170 days frequency. In the Sudan Savannah and the Sahel, the frequency will be increasing from 40 to 60 and 100 days in the Western part of the Sahel.

The Figure 4.37 shows the same pattern of aerial change in the future frequency of HWs in Nigeria under RCP8.5. The peak is observed in the Coastal zone with 170 days and 120-140 days in the Tropical Rainforest and Guinea Savannah. The Sahel will remain between 40 and 60 days to 2068, date after which the frequency will be increasing and cover all the Northern part (Sahel) especially from 2073. From 2073, many States in the Tropical Rainforest and Guinea Savannah will experience high frequencies of HW namely, Niger, Kwara, Oyo, Osun, Ekiti, Kogi, Nassarawa, Benue, Taraba, Ebonyi and Enugu States among others like showed in Figure 4.37. From 2063 the Coastal zone will be experiencing between 0 and 40 HWF.

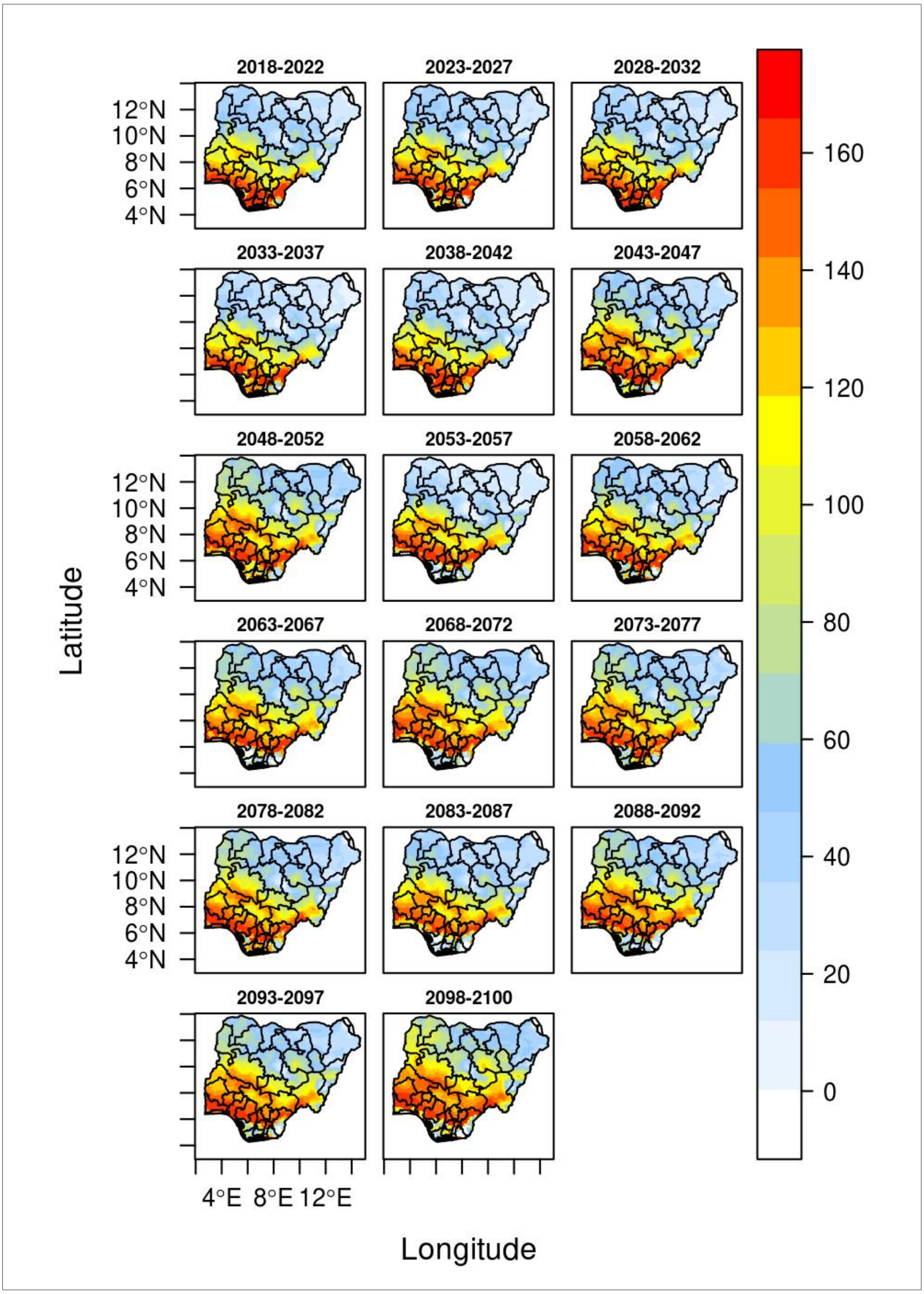

Figure 4.36 Heat Wave Frequency (HWF) using TX90 in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

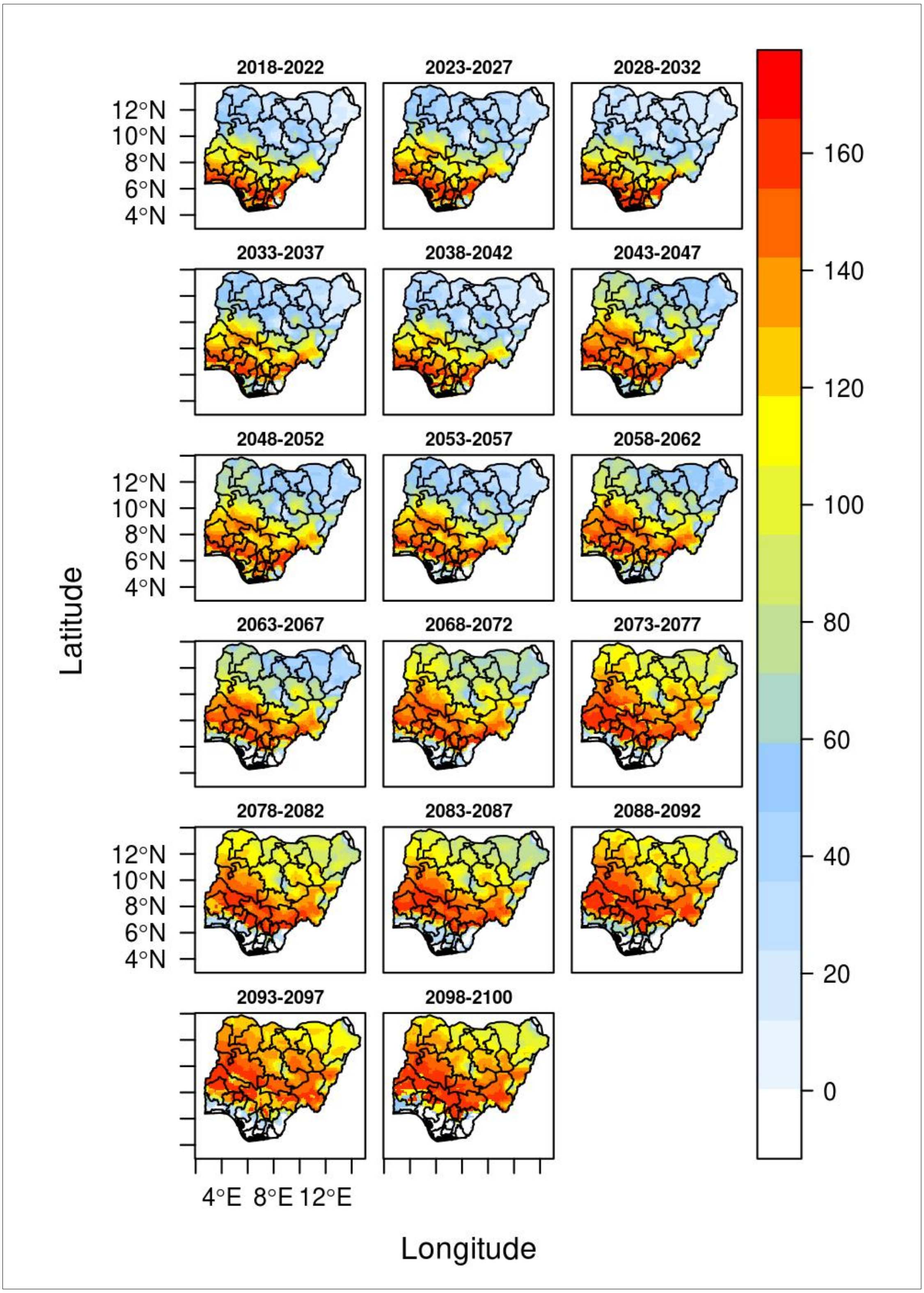

Figure 4.37 Heat Wave Frequency (HWF) using TX90 in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

HWF using TN90 definition under RCP4.5 present high values in the Coastal zone throughout the period of prediction (Figure 4.38). The frequency shows 160 days in the Coastal zone while the Tropical Rainforest, the Guinea Savannah and the Sudan Savannah will record 50 days, 40 days and 20 days respectively. The Sahel will have the lowest HWF. Over the time the frequency will increase in each of the climatic zones except the Coastal zone that will have the highest HWF of 140-170 days.

Under RCP8.5 (see Figure 4.39), the Coastal zone will have the highest HWF (120-160) only from 2018-2062. During that period the Tropical Rainforest, the Sahel, the Sudan Savannah and the Guinea Savannah will experience frequencies between 20 and 60 days. From 2073 the Guinea Savannah will experience high frequencies in different States even the Sahel will be affected by frequencies of 140 to 150 in the West.

The frequency of HWs in the extreme scenarios will be increasing and cover more zones with high values. The frequency is a very important indicator of HW.

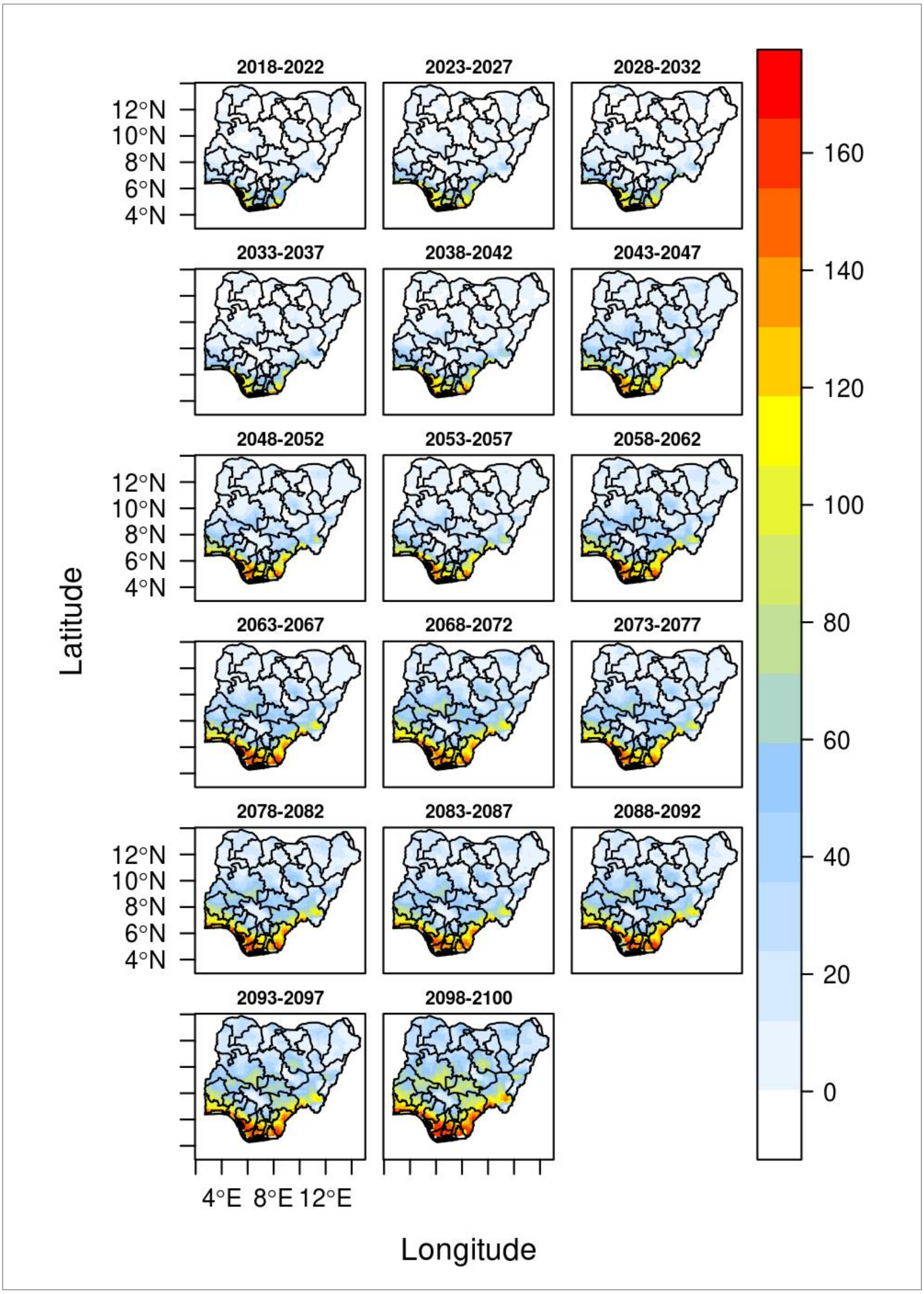

Figure 4.38 Heat Wave Frequency (HWF) using TN90 in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

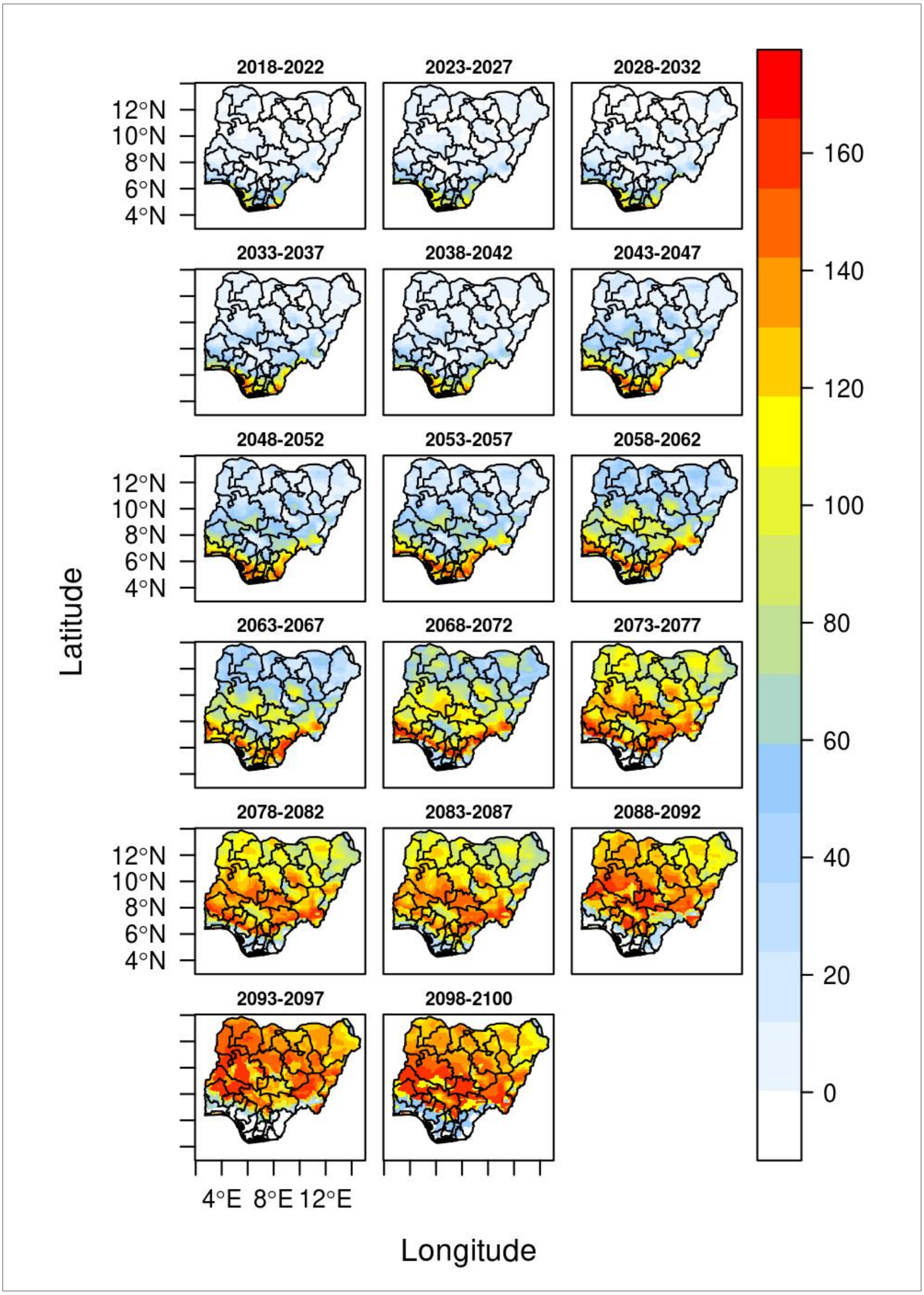

Figure 4.39 Heat Wave Frequency (HWF) using TN90 in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

The prediction of HWF using EHF under RCP4.5 gives similar results to the previous HW definitions. The major zones that will be highly affected (HWF > 100 days) are the Coastal, Tropical Rainforest and Guinea Savannah. The Figure 4.40 shows the frequency of HWs in Nigeria from 2018-2100 where the Sahel will experience less than 70 days frequency. The Coastal zone will experience from 2063 frequencies less than 50 days. A belt of 160 days joins the two sides of the study area from West to East in the Tropical Rainforest. The period 2098-2100 will particularly affect the Tropical Rainforest and the Guinea Savannah with high frequencies and Niger State is part of the States that will be seriously affected.

The RCP 8.5 shows in the picture Figure 4.41 a more critical scenario of HWF. The highest value is maintained at 170 days but the coverage of high frequencies will increase. From the year 2018, the Coastal and Tropical Rainforest will be affected by 110-160 days frequency. The belt of 160 days frequency that joins the two sides of Nigeria from West to East will still be there in the Coastal and Tropical Rainforest. From 2043 the Tropical Rainforest and the Guinea Savannah will be covered by 120 to 160 days HWF and from 2068 the same HWF will cover all the Sahel and almost all the whole country will experience high HW frequencies during the period 2068-2100 except the Coastal zone that will experience almost no HW. During 2088-2097 even the Tropical Rainforest will be spared.

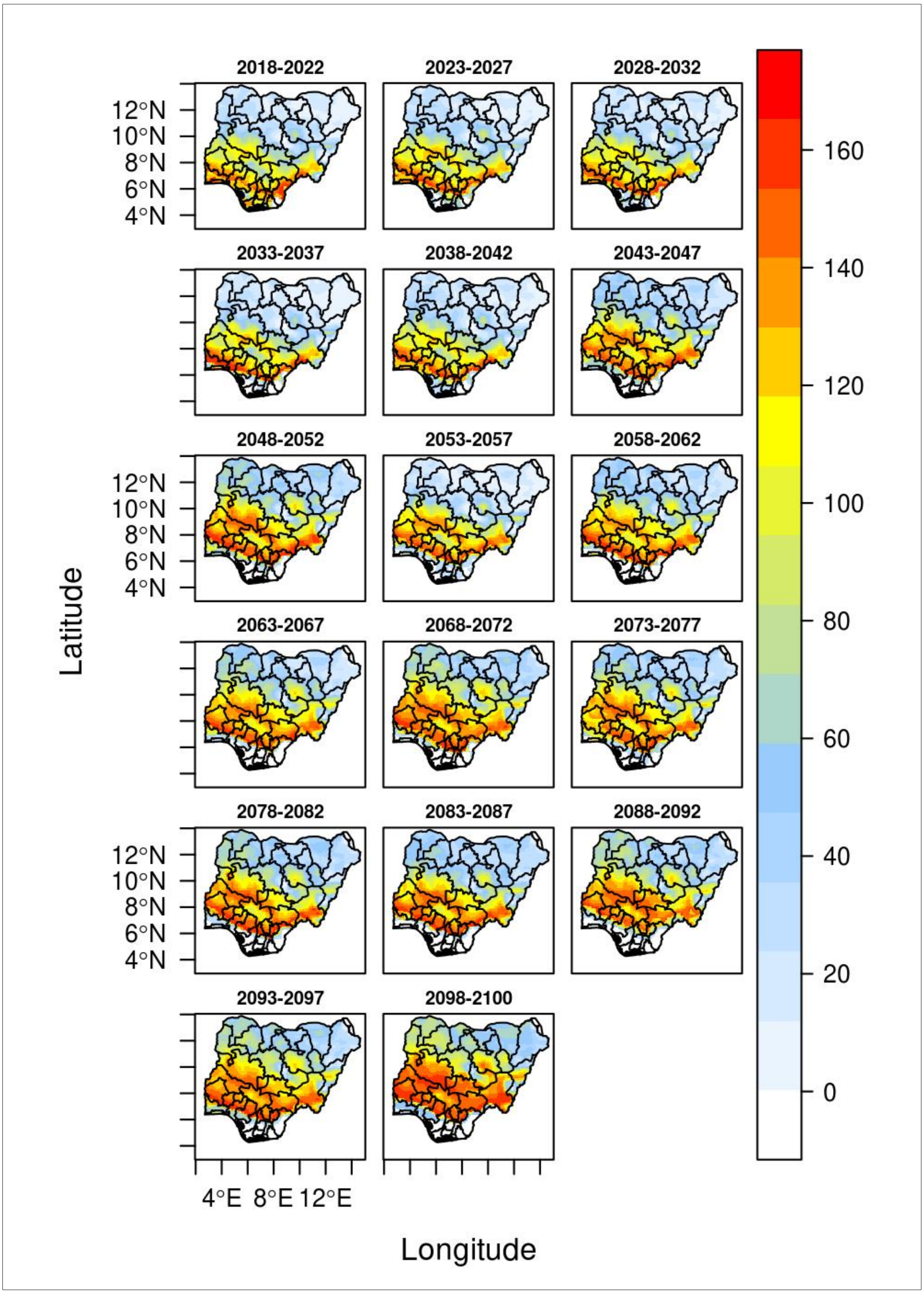

Figure 4.40 Heat Wave Frequency (HWF) using EHF in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

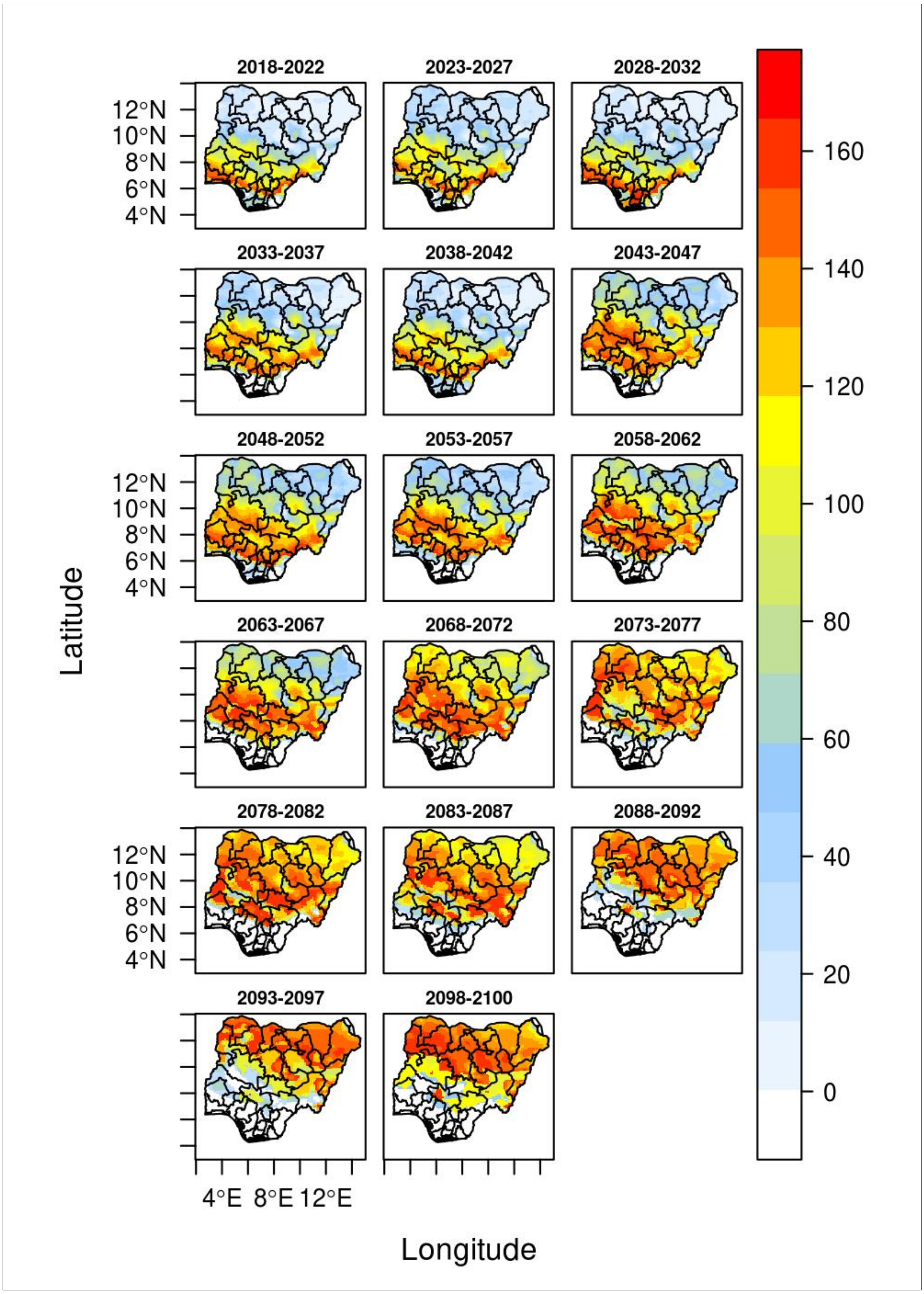

Figure 4.41 Heat Wave Frequency (HWF) using EHF in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

4.3.5 Heat Wave Amplitude (HWA) for TX90, TN90 and EHF

The hottest days of the hottest HW using TX90 under RCP4.5 vary from 26 °C to 45 °C. Figure 4.42 shows 40-42 °C in the Sahel, the Sudan Savannah and the Northern part of the Guinea Savannah. An average of 30 to 34 °C will be maintained at Jos Plateau and vicinities as well as the Tropical Rainforest and the Coastal zone. The high amplitudes that are observed in the Sahel will increase over time especially from 2048. The amplitude will increase to 45 °C in the Sahel within the period 2083-2100. With the RCP8.5 the same pattern is observed but the Sahel will reach the highest values of amplitude sooner than the RCP4.5, in 2078. The variation range of the amplitude is ~29 to 46 °C.

The Figure 4.43 shows clearly the details of the aerial coverage and the associated amplitudes. The RCP8.5 will be identical to the RCP4.5. The Sahel will experience high amplitudes from 2078.

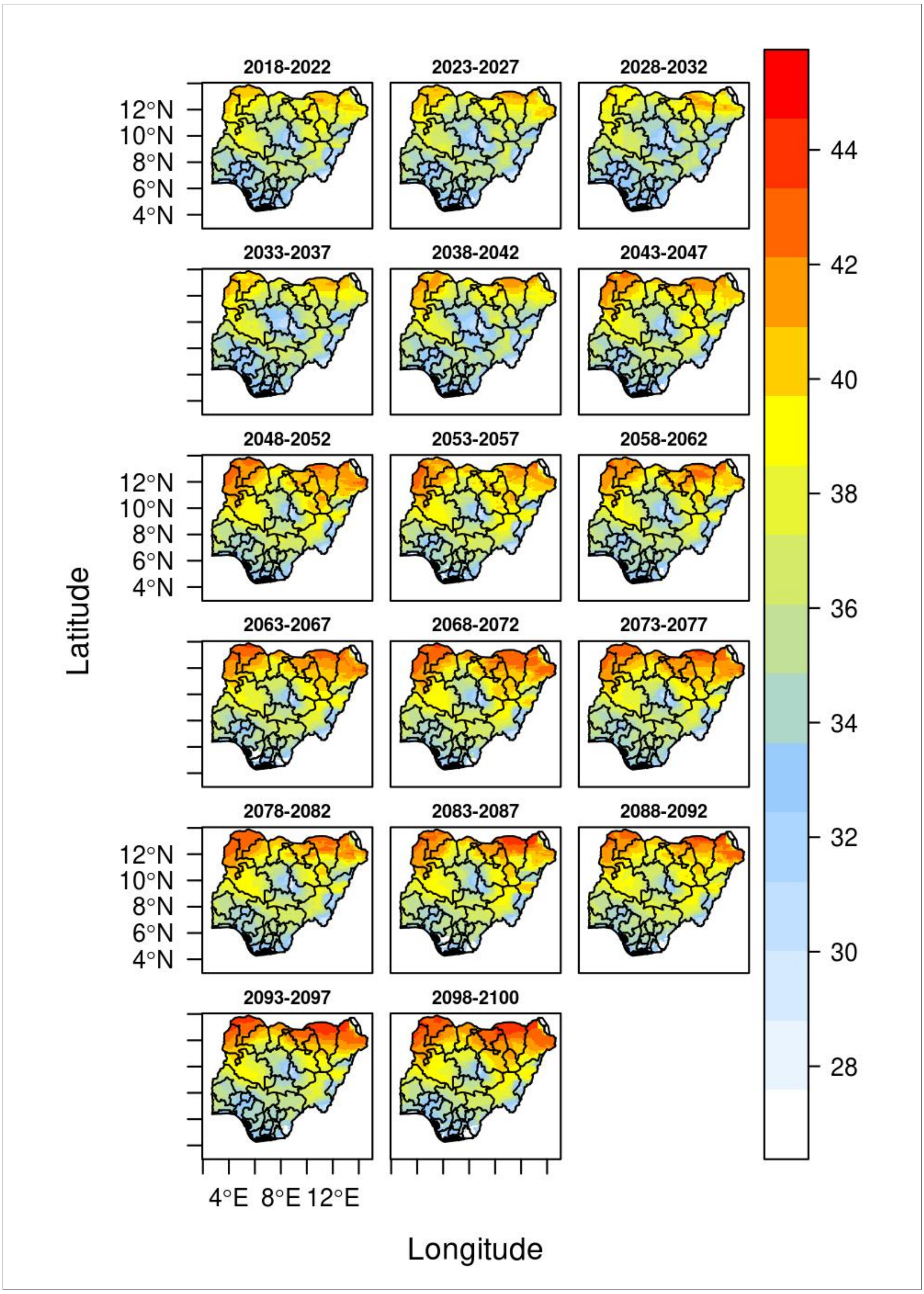

Figure 4.42 Heat Wave Amplitude (HWA) using TX90 in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

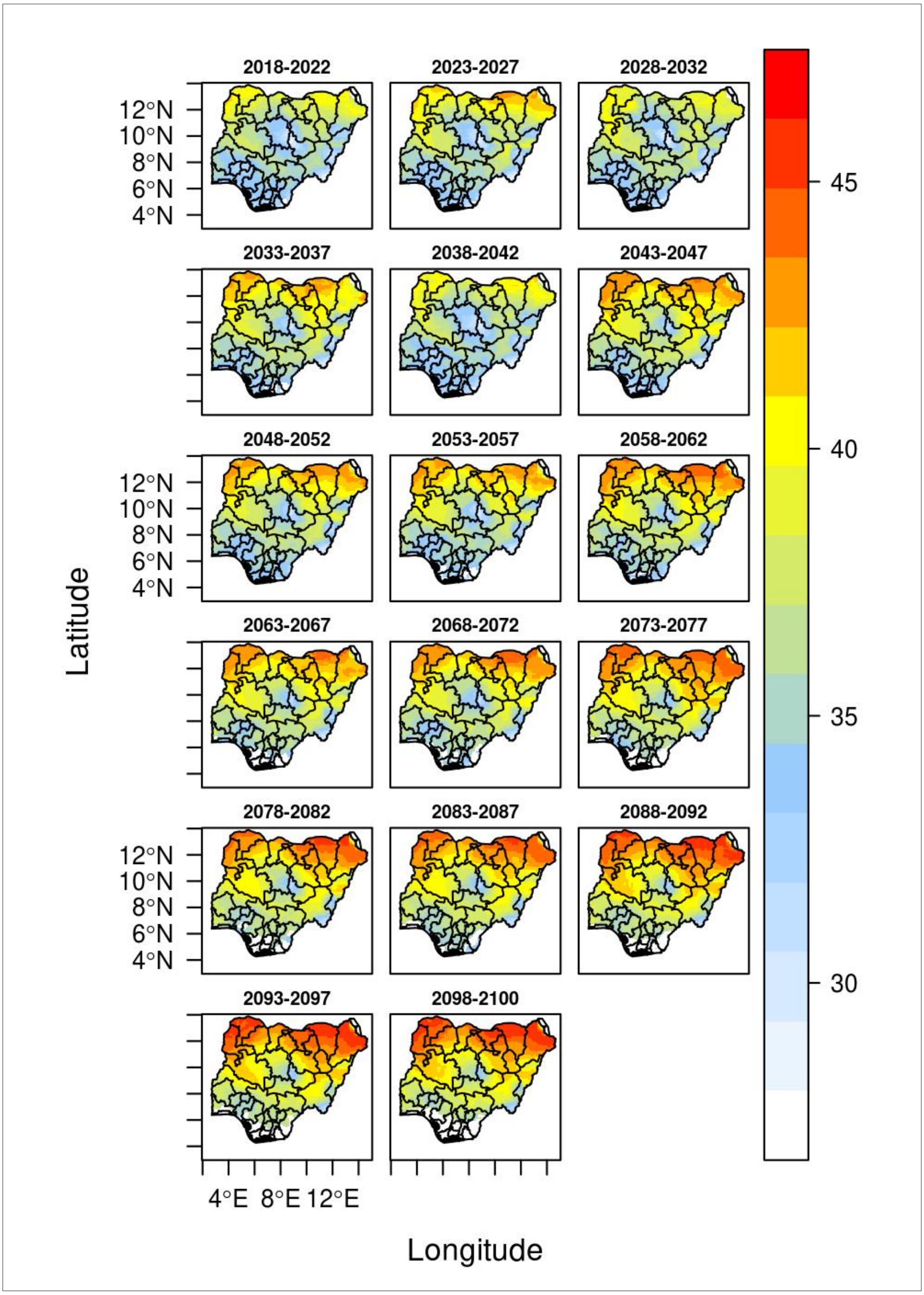

Figure 4.43 Heat Wave Amplitude (HWA) using TX90 in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

For TN90, HWA has a maximum of 32 °C that is observed in the Sahel from 2048. The 32 °C will affect five (5) States (sokoto, Kebbi, Jigawa, Yobe and Borno) from 2083. The amplitude as well as the aerial coverage will increase over time from 2018 to 2100 in the Sahel from an average of 28 °C to 30 °C as shown in the Figure 4.44. The Guinea Savannah will observe also an increase in the amplitude of HWs as well as the Sudan Savannah. The Coastal zone will have a higher amplitude of HWs than the Tropical Rainforest. The Jos Plateau will maintain the current hilly climate in place, a very low amplitude till 2072. The vicinities of the Plateau will have higher amplitudes. The general tendency shows an increase of the temperature from the Coastal zone to the Sahel except for the Jos Plateau.

The RCP8.5 will have the same pattern, the amplitude will vary from 18 to 34 °C. The peak will be observed from 2088 in the same States like in RCP4.5. The Jos Plateau will maintain an average amplitude of 22 to 24 °C. From 2093 to 2097 the Coastal zone will not experience high HWs, the amplitude will be less than 19 °C. The Sudan Savannah, the Guinea Savannah and the Tropical Rainforest will have increasing amplitudes Figure 4.45.

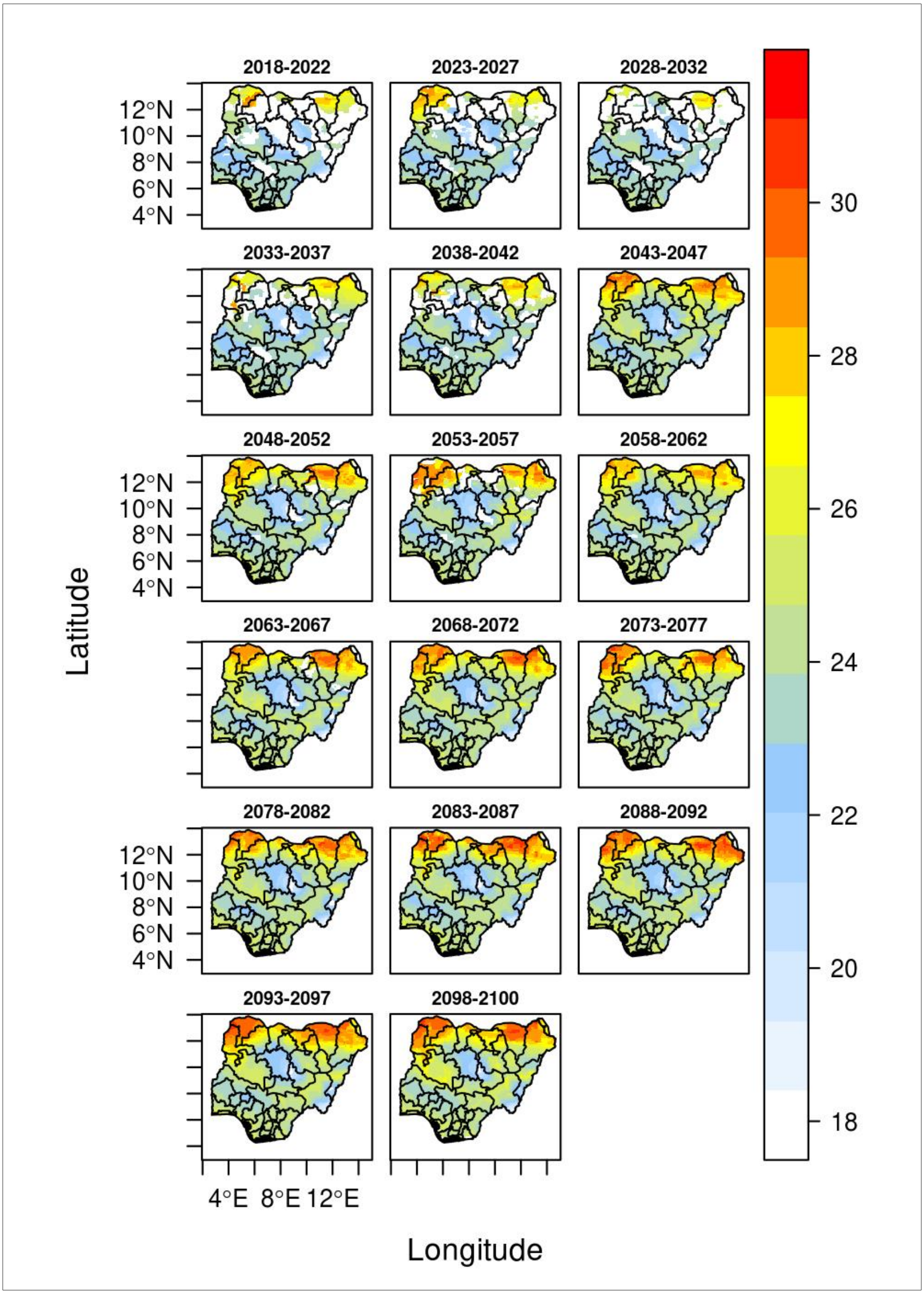

Figure 4.44 Heat Wave Amplitude (HWA) using TN90 in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

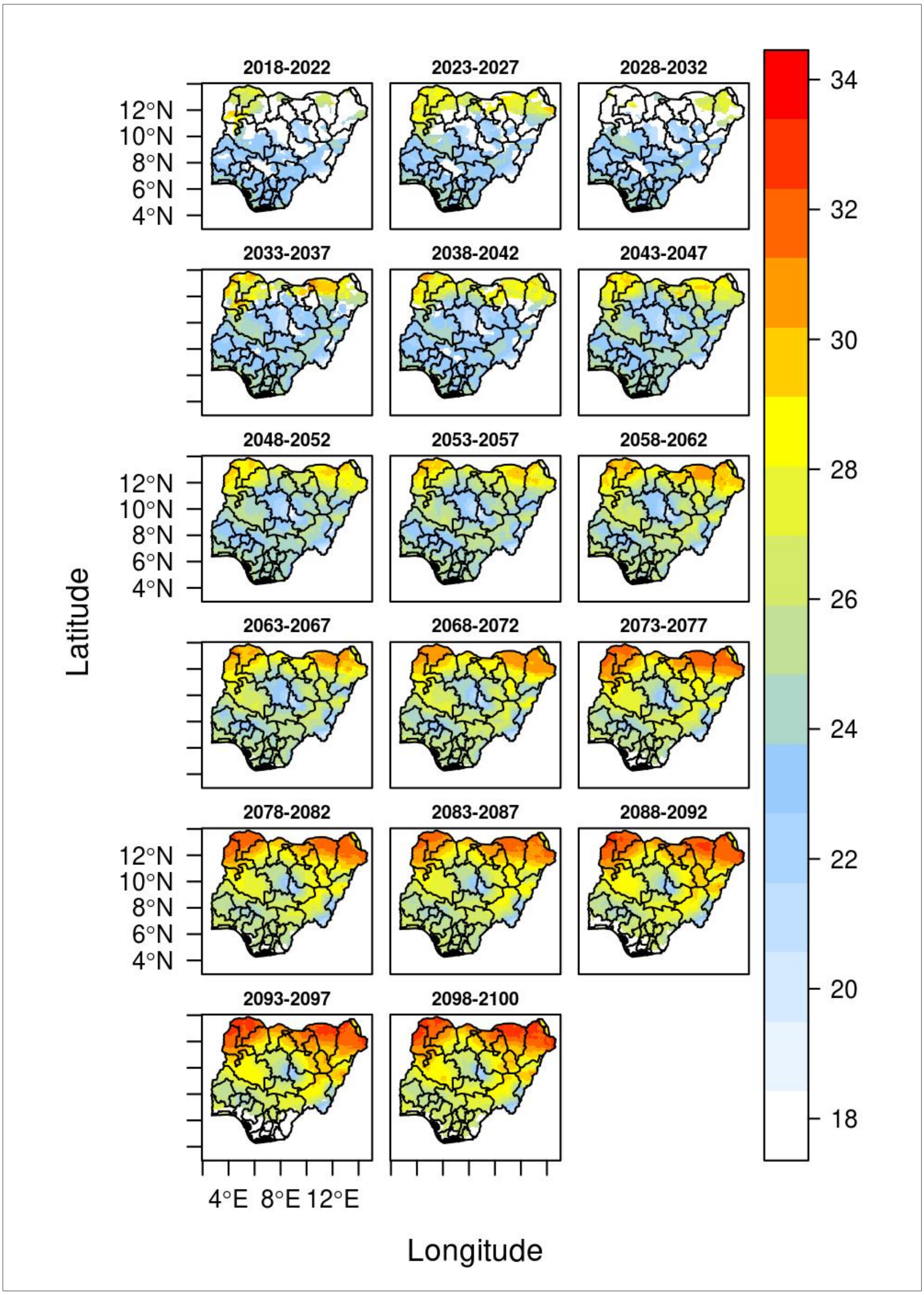

Figure 4.45 Heat Wave Amplitude (HWA) using TN90 in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

The Amplitudes will be lower according to the Excess Heat Factor under RCP4.5. They will vary from 0 °C^2 to 10 °C^2. The average amplitude will be between 2 °C^2 and 4 °C^2 except for some States like Niger, Kwara, Oyo, Kogi, Benue and Taraba where some locations will experience amplitude of 6 °C to 7 °C^2 from 2018. This amplitude will increase in those States over the time and other States in the Sahel will be affected from 2048 as it is captured in Figure 4.46. The period 2088-2092 will be particularly critical for Niger State and some other States in the Guinea Savannah. Under RCP8.5 the whole Nigeria will be covered by HWA of 5 °C to 6 °C^2.

The tendency in Figure 4.47 shows an increase of the amplitude in the Sahel, the Sudan Savannah and the Guinea Savannah from 2073 to 2077 but for the Coastal zone the HWA will be 0 from 2053 and this will expand across the Tropical Rainforest from 2093. The peak (17 °C^2) will be reached during the period 2093-2097 in Niger, Abuja (FCT), Nassarawa and Taraba States within 2098-2100. All the States that will be affected are located in the Guinea Savannah.

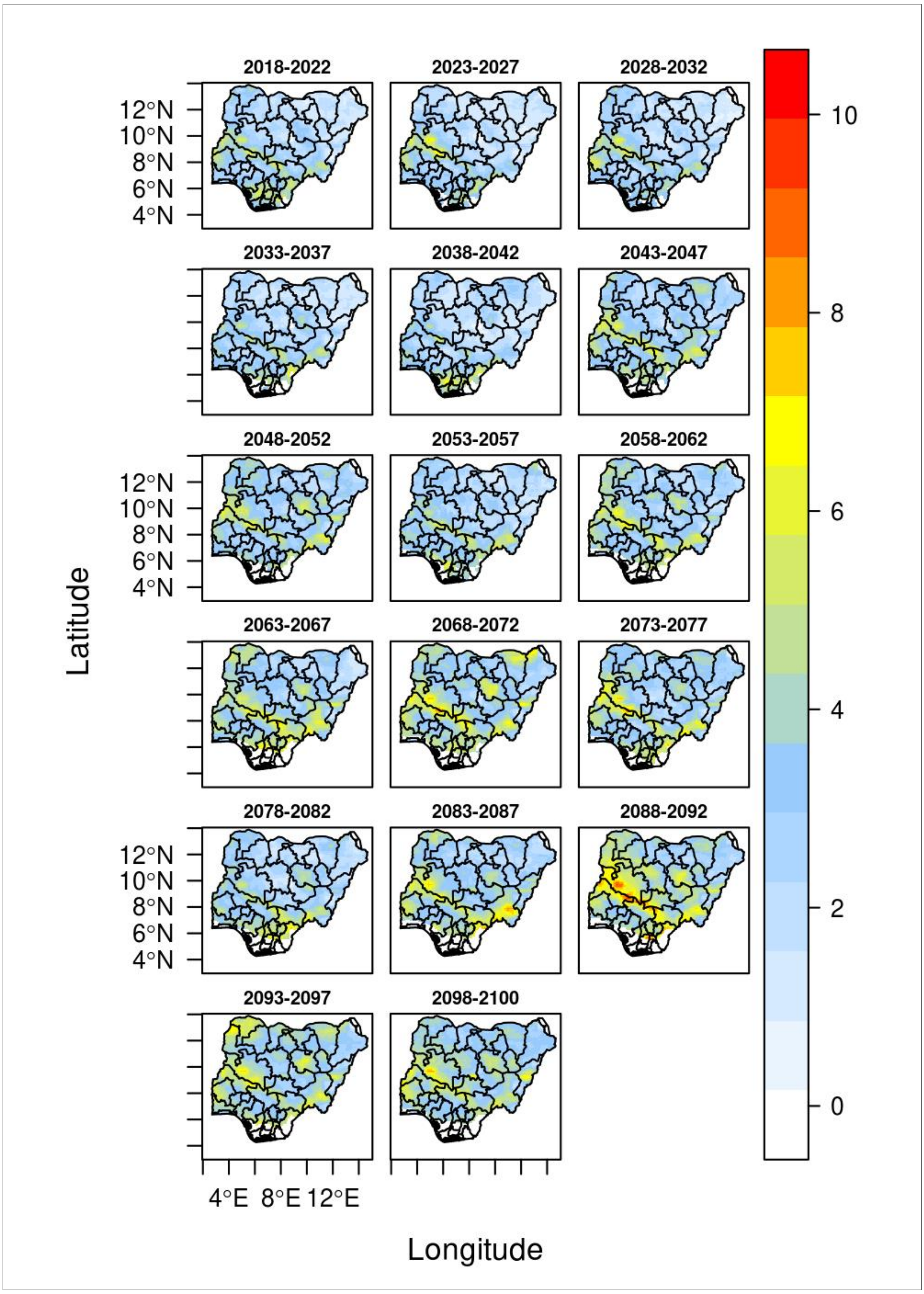

Figure 4.46 Heat Wave Amplitude (HWA) using EHF in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

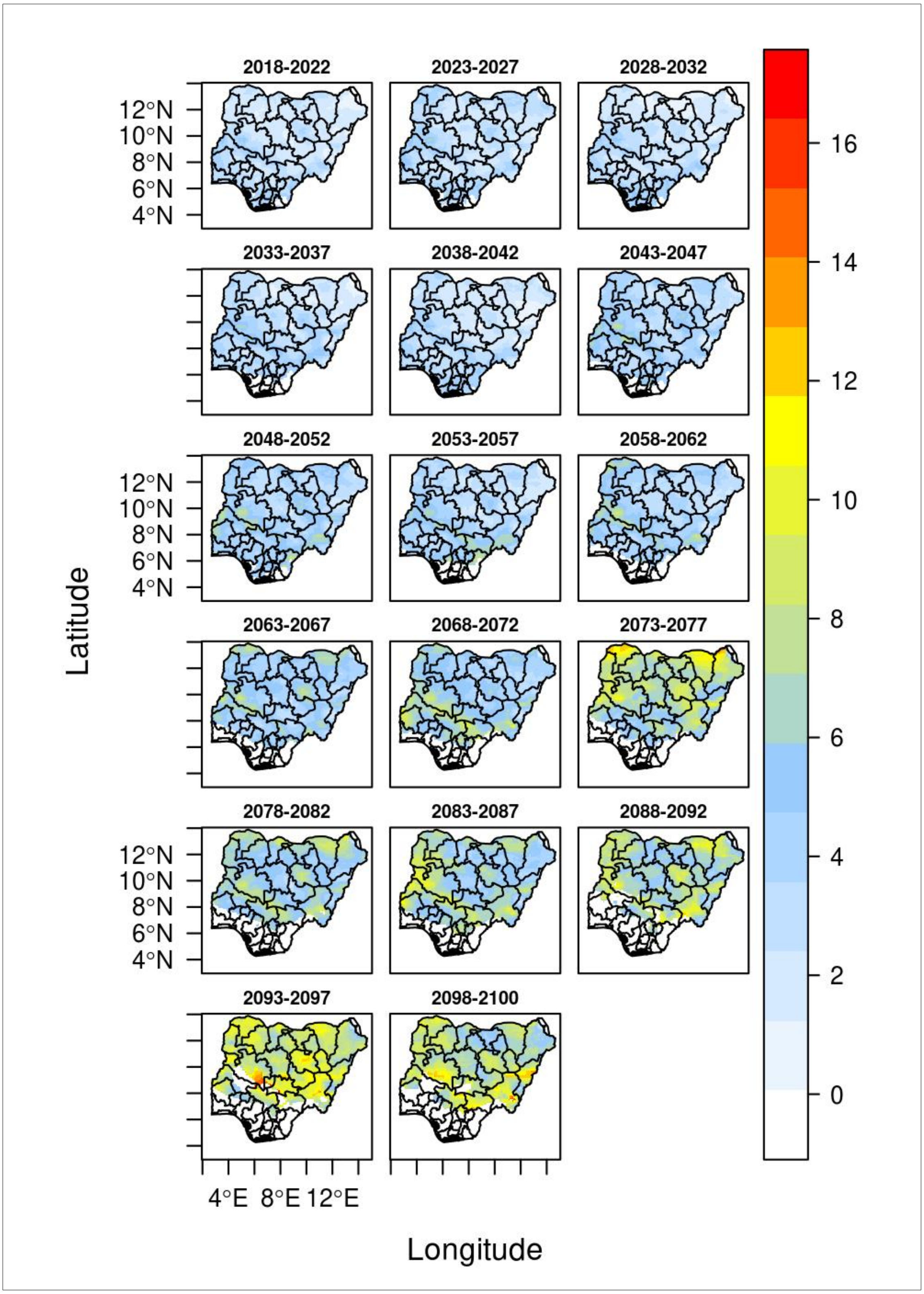

Figure 4.47 Heat Wave Amplitude (HWA) using EHF in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

4.3.6 Heat Wave Magnitude (HWM) for TX90, TN90 and EHF

The HWM is one the most used characteristic when measuring HWs. The future HWs magnitudes were computed in the study using the three (3) definitions (TN90, TX90, and EHF) under the two scenarios (RCP4.5 and RCP8.5). Also, the Heat Wave Magnitude Index daily (HWMId) was computed for comparison in the different climatic zones of Nigeria and with the worldwide recorded HWs.

The TX90 under RCP4.5 shows in the Figure 4.48 from 2018 to 2100, a minimum HWM of 26 °C and the maximum of ~ 41 °C. The Sahel will show the highest values throughout the period. The HWM will be increasing in the Sahel from 37-39 °C in 2018 to 41 °C in 2063. The Eastern part of the Sahel will record higher HWM than the Western part especially in Borno and Yobe. The rest of the zones will also experience a general increase in the magnitude of HWs. The Plateau of Jos will keep the lowest records with the Coastal zone when the magnitude will be increasing in the country.

There is no difference in the magnitudes of HWs in Nigeria under the two scenarios. The results got with the RCP4.5 were the same with the ones got under RCP8.5. The magnitude under RCP8.5 in Figure 4.49 will reach 42 °C from 2070 but the increase will start from 2033 especially in 2043.

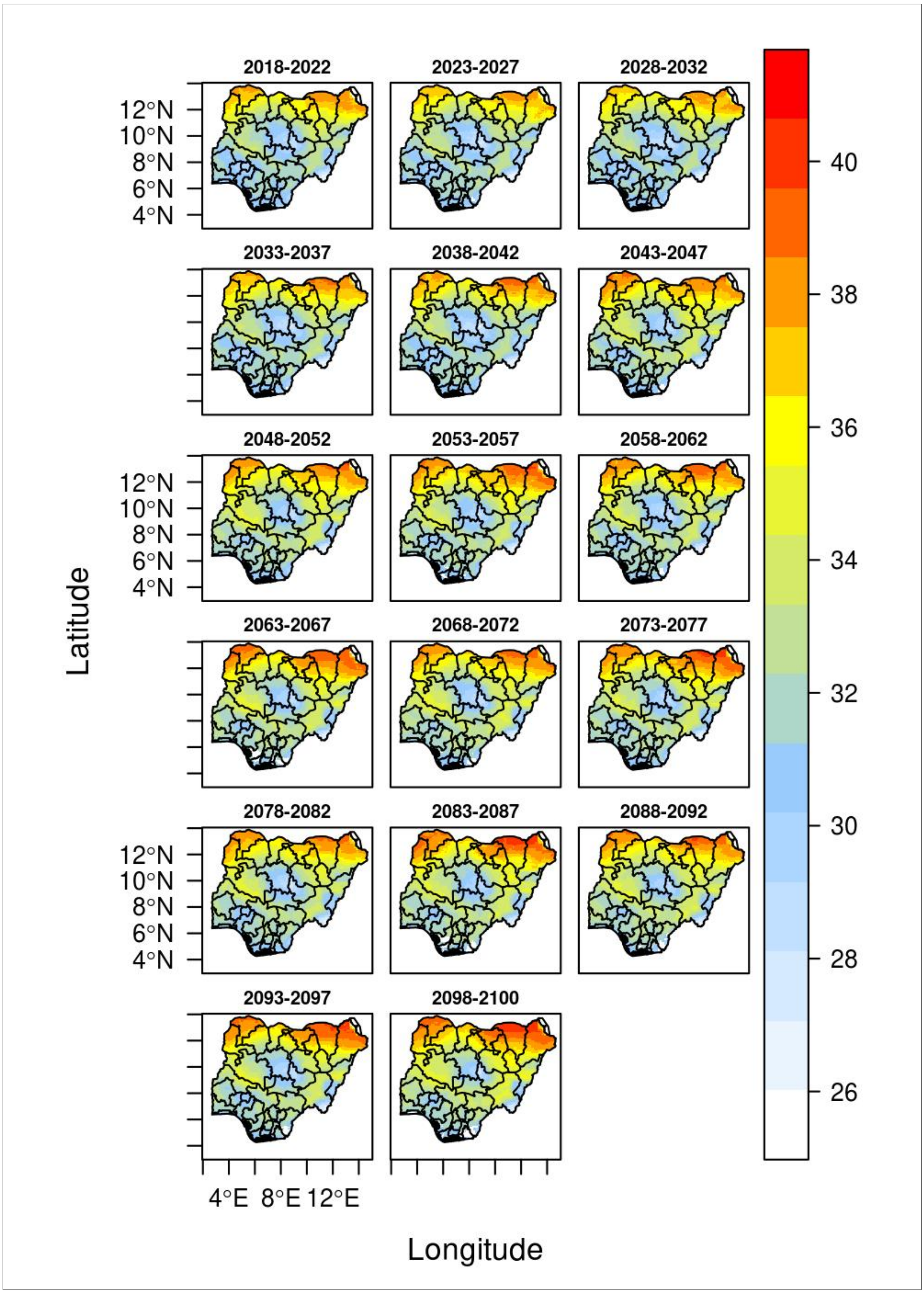

Figure 4.48 Heat Wave Magnitude (HWM) using TX90 in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

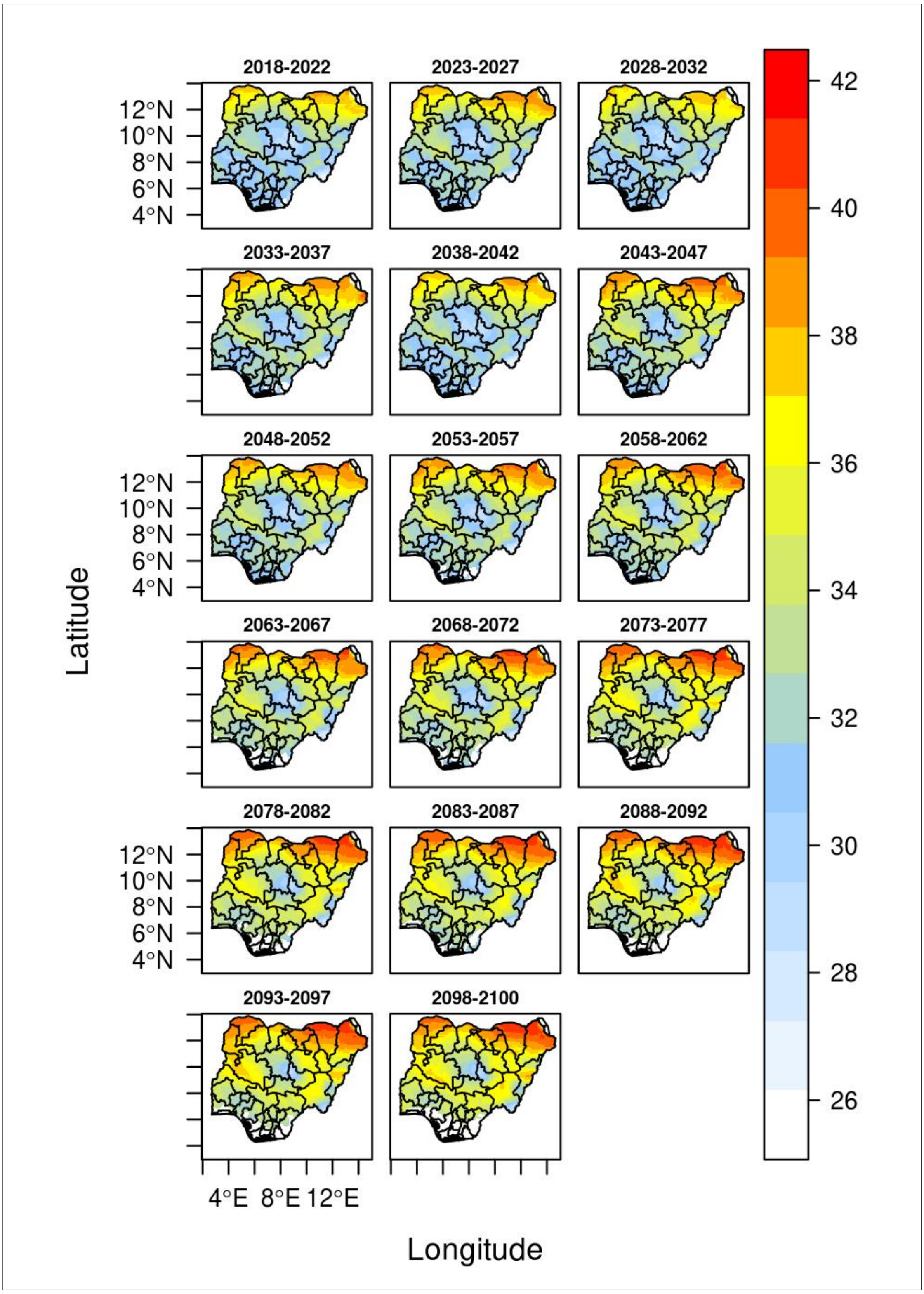

Figure 4.49 Heat Wave Magnitude (HWM) using TX90 in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

The minimum temperature will have a less dramatic face. The HWM with TN90 in Figure 4.50 shows HW of magnitude 18-30 °C. The Sahel will still maintain the highest records but in only some area, the extreme Western and Eastern parts of the Sahel affecting mainly Borno, Yobe, Sokoto Kebbi and Zamfara States from 2018 to 2047. The Coastal area will be totally covered by HWM of 24 °C from 2018 while the Tropical Rainforest, the Guinea Savannah and the Sudan Savannah will have partial aerial coverage from 2018 to 2042. From 2068, all the zones are covered and the Sahel will be well delimited as the highest HWM zone with 26 to 28 °C. The peak will be reached in the many States in the Sahel during the period 2053-2057.

Under RCP8.5 the pattern will be the same with RCP4.5 as shown in the Figure 4.51. The intensity and the aerial coverage will increase in the future from 2043. The Coastal zone will vary between 24 and 26 °C. In the Guinea Savannah, Niger State, Nassarawa, Taraba and Adamawa States will have the highest HWM (26-28 °C).

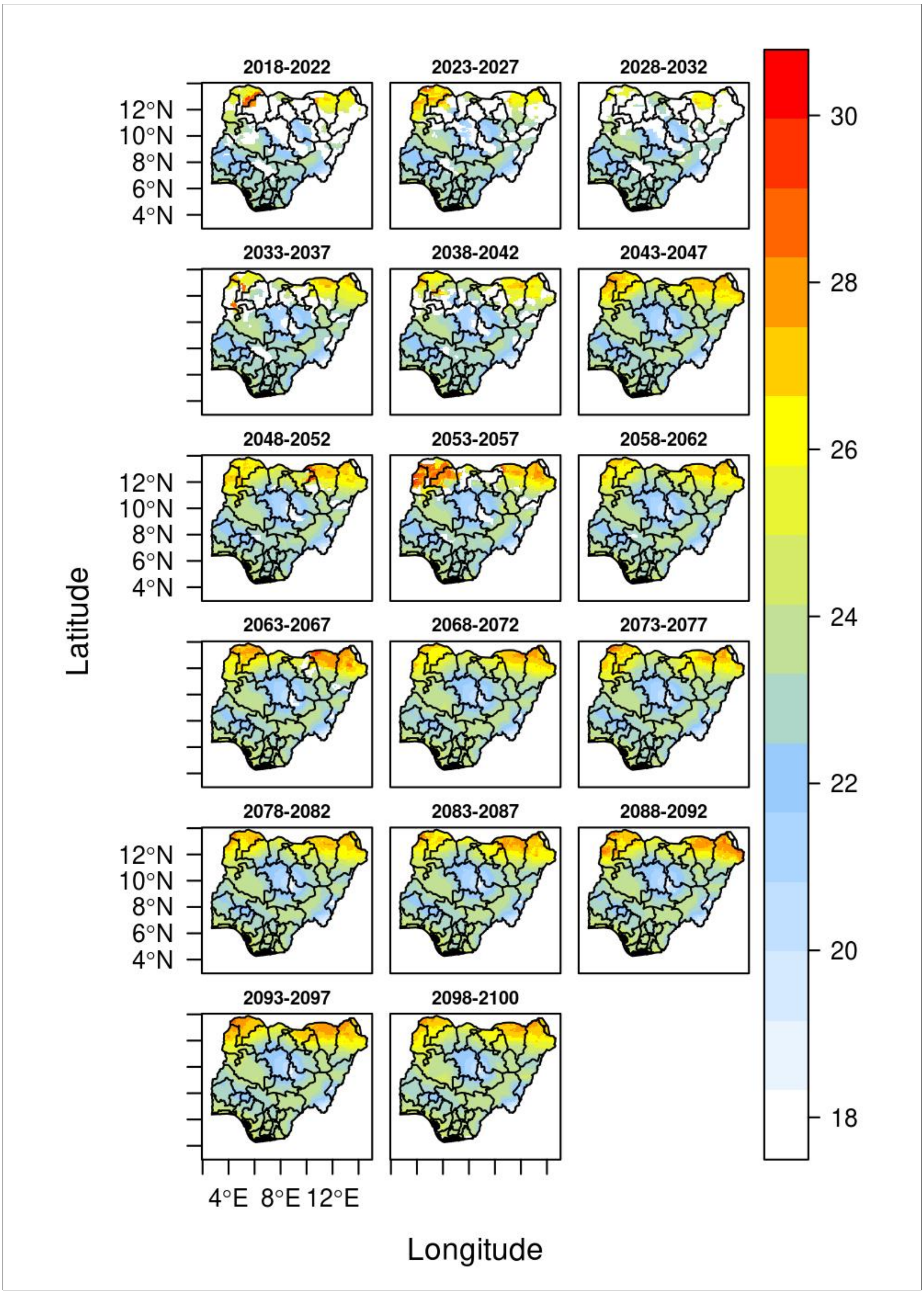

Figure 4.50 Heat Wave Magnitude (HWM) using TN90 in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

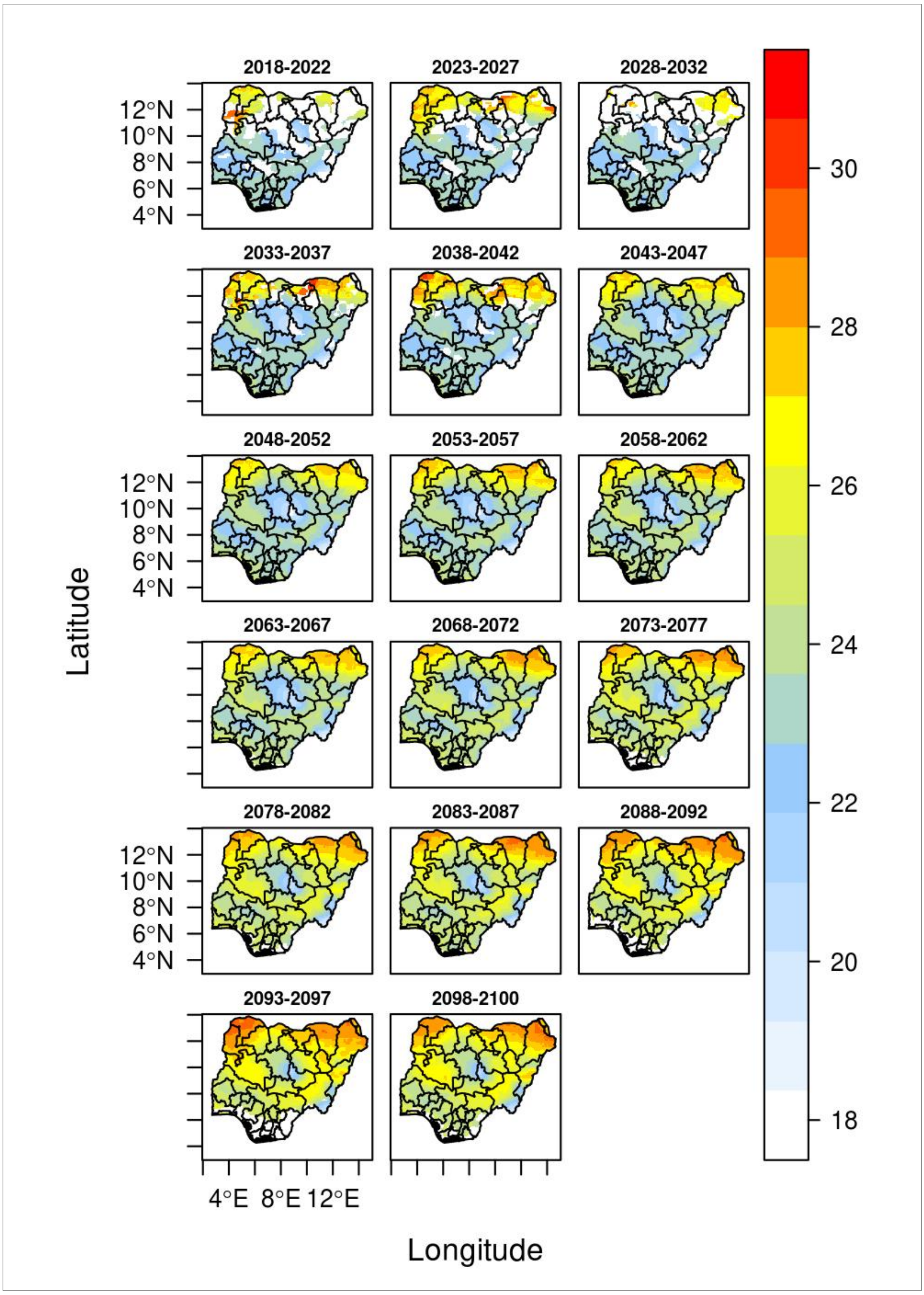

Figure 4.51 Heat Wave Magnitude (HWM) using TN90 in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

The EHF reveals in the Figure 4.52 very low HWM under RCP4.5. The average values in all the zones will be 1 °C^2 except for the Coastal zone where the magnitude will be higher than in the other zones. From 2018 the Coastal zone will be recording between 1.5 °C^2 and 2 °C^2. The Coastal zone's values will be moving progressively to the Tropical Rainforest leaving the Coastal zones with a HWM = 0. This can be understandably observed from 2063. Niger, Kwara, Nassarawa, Benue and Taraba States will be particularly affected in the Guinea Savannah. The peak will be reached during the period 2053-2057 in the Guinea Savannah especially between Kaduna and Plateau, but the coverage will be very small.

Under RCP8.5 the Coastal zone will have a low HWM (0.5-1 °C^2) from 2018-2047. The other zones will have during the same period 1.3 °C^2. From 2048-2057 the Eastern Coastal part will have 2.0 °C^2 of magnitude mainly in Ogun, Ondo, Delta, Bayelsa and Rivers States. From 2058 the Coastal zone will have 0 °C^2 of magnitude while many other States will see their magnitude increased especially from 2073. From 2093 many States in the Guinea Savannah, Sudan Savannah and the Sahel will be affected by HWs of magnitude 2.7 °C^2. During the last period (last panel of 3 year average in Figure 4.53) Niger State and Taraba will record in the Guinea Savannah the highest magnitude (4 °C^2). Many States in the Coastal and Tropical Rainforest will be having less than 0.1 °C^2.

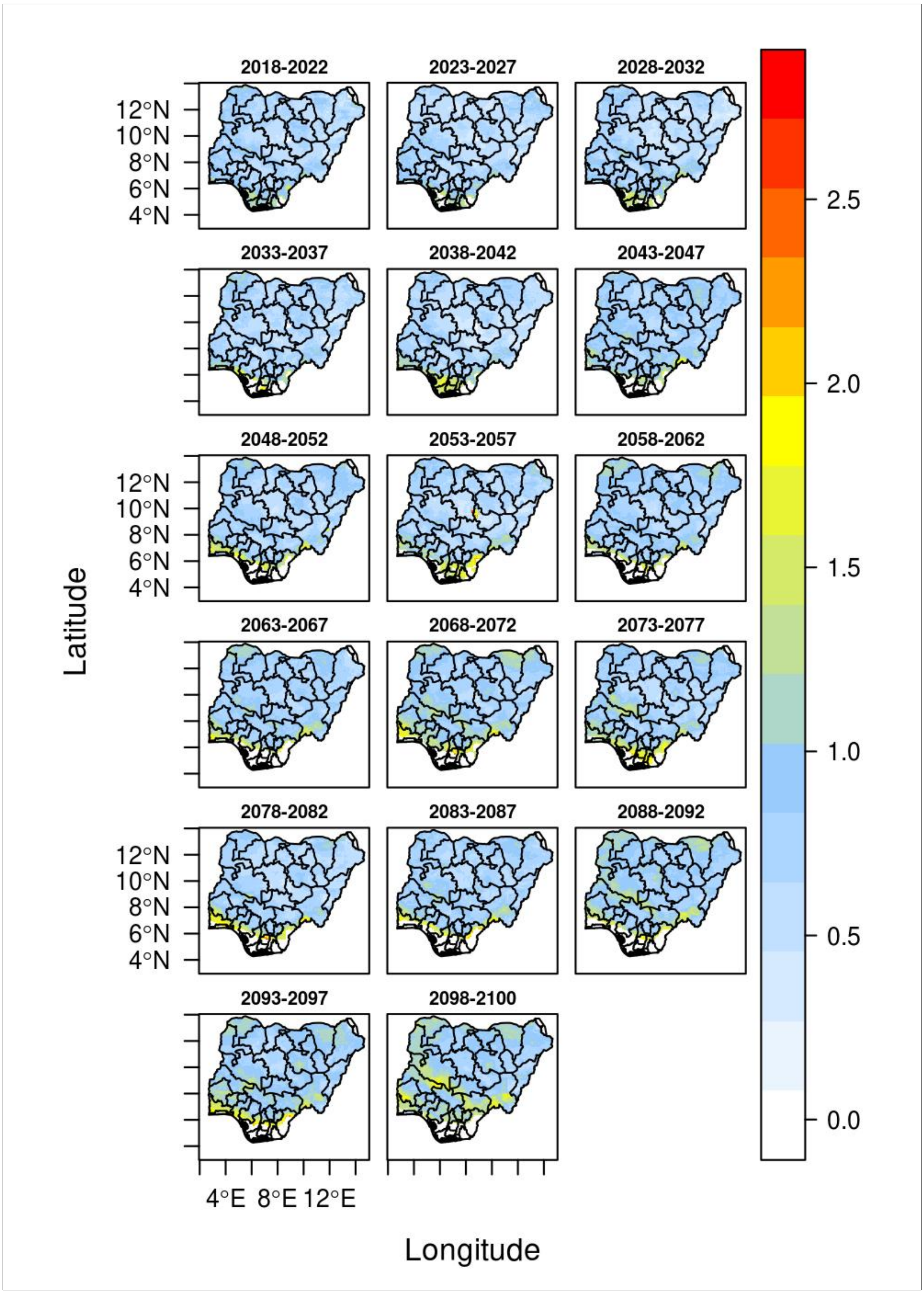

Figure 4.52 Heat Wave Magnitude (HWM) using EHF in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

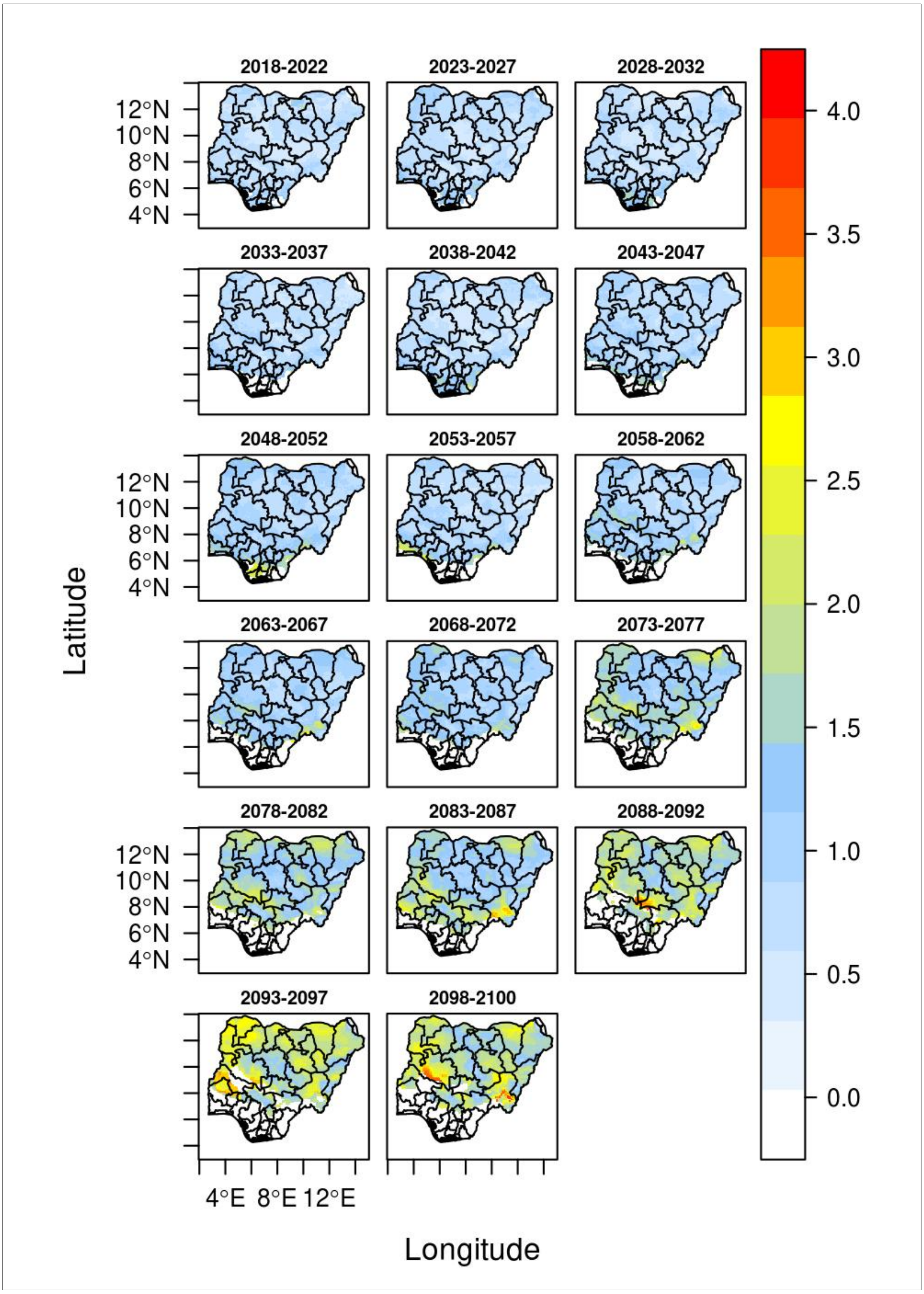

Figure 4.53 Heat Wave Magnitude (HWM) using EHF in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

The Heat Wave Magnitude Index daily (HWMId) shows the same pattern previously observed for HWM using EHF. The Figure 4.54 shows the 5 years average pattern of future HWM from 2018-2100 using minimum temperature ($HWMId_{tn}$). From 2018 there will be no important magnitude of HWs till 2038 where the South (Coastal zone) will start experiencing very extreme HWs (magnitude 14). From 2068 very extreme HWs will affect many States in the Coastal zone as well as the Tropical Rainforest and the Guinea Savannah. The year 2068 will also record in the Coastal zone super extreme HWs in Cross River, Akwa Ibom, Rivers States and the South of Ondo State. The aerial coverage in each of the States is very small. The Sudan Savannah and the Sahel will have normal conditions ($HWMId_{tn}$ less than 1).

Under RCP8.5 in Figure 4.55, there will be no important weather condition till 2033 where the $HWMId_{tn}$ in the Coastal zone will be 14 (very extreme HW). The situation will start being critical from 2048, with very extreme HWs in the Coastal and Tropical Rainforest. Ultra extreme HWs will be observed in the Coastal zone from 2058. The ultra HWs will increase the aerial coverage and affect many other States in the Tropical Rainforest and the Guinea Savannah, even the Sahel will be affected from 2078. In 2093 almost the whole country will experience high magnitude HWs except for the Coastal zone and Tropical Rainforest where there will be normal HWs conditions.

This pattern of moving space in the occurrence of HWs in the future, is similar to results of HWM for EHF. The difference is in the values of the magnitude. As a comparison, the EHF performs good.

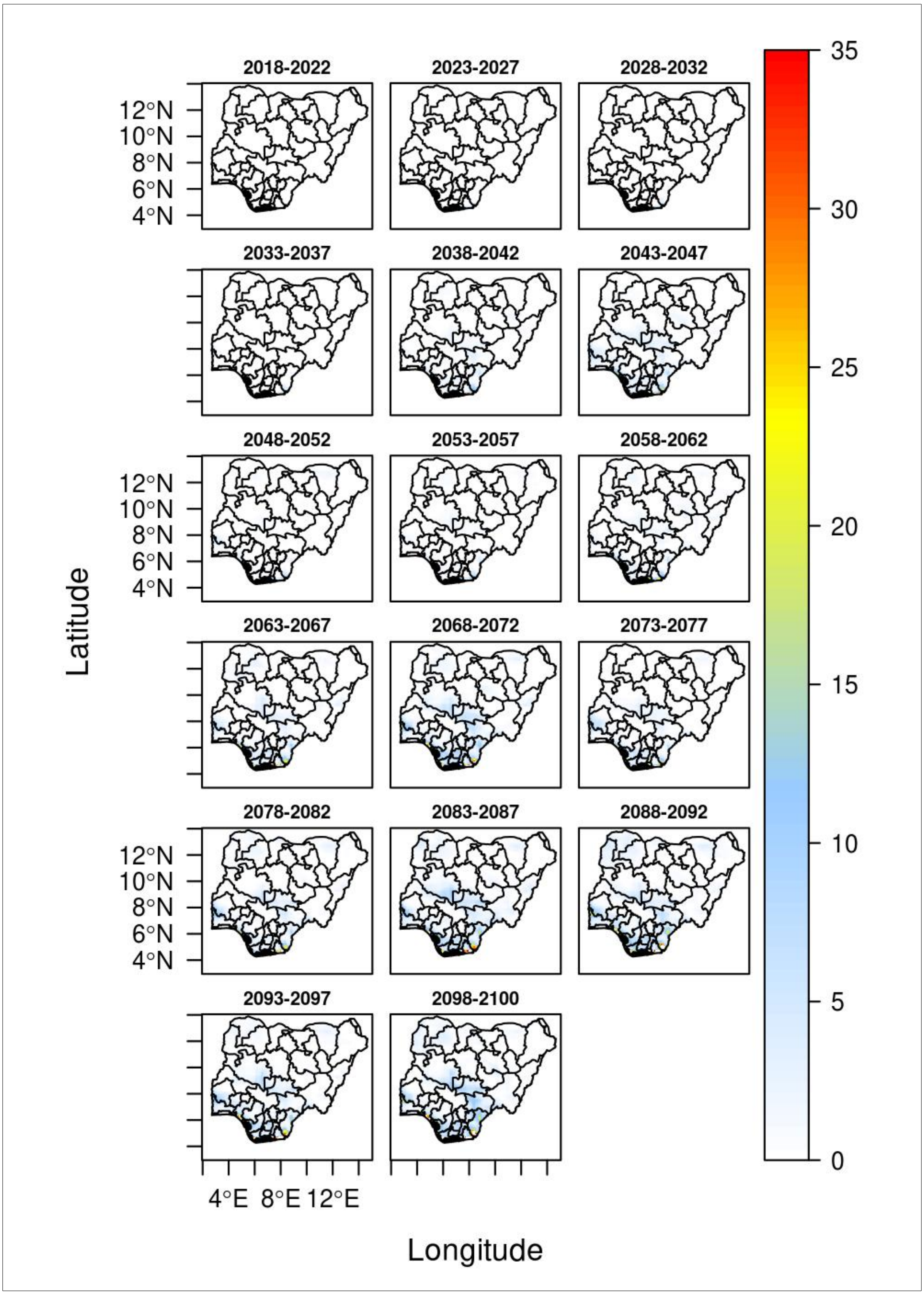

Figure 4.54 Heat Wave Magnitude (HWM) using HWMId on TN ($HWMId_{tn}$) in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

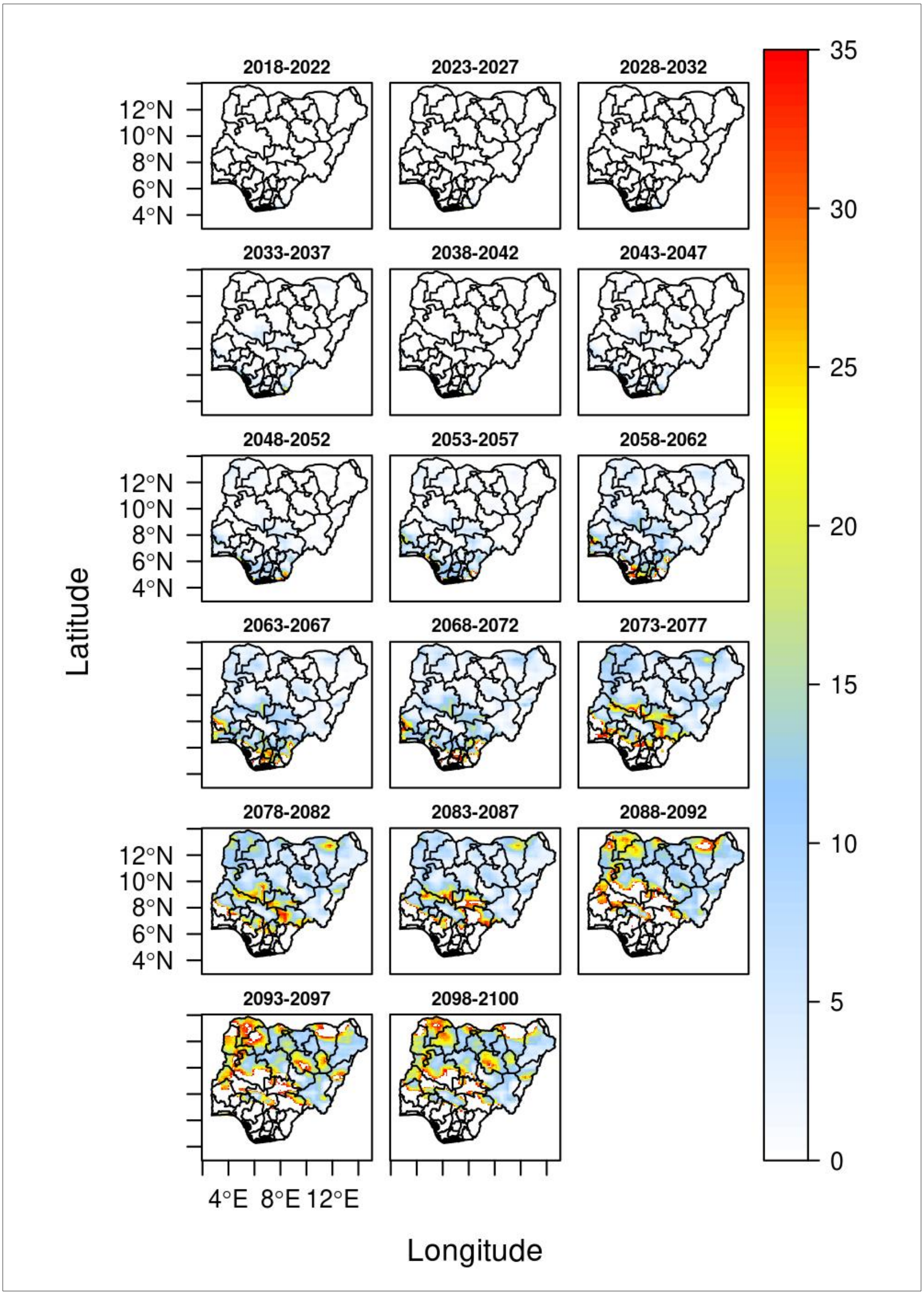

Figure 4.55 Heat Wave Magnitude (HWM) using HWMId on TN ($HWMId_{tn}$) in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

The HWMId for TX ($HWMId_{tx}$) in Figure 4.56 show more drastic conditions. From 2018, the Coastal zone, mainly Ogun and Cross River States, will experience almost at that time super extreme HWs. The other zones will have normal conditions and this till 2038. The coverage area of super extreme HWs will increase in the Coastal zone. From 2040 the Tropical Rainforest will also be affected with some States in the Guinea Savannah. All the States will be getting affected over time. From 2093, Niger State, and some States in the Guinea Savannah will be affected by very extreme HWs. The Sahel will be experiencing from normal to extreme HWs.

Under RCP8.5, like with the TN, the conditions will be severely harsh. The Figure 4.57 shows the same pattern and magnitude of HWs from 2018 as in the RCP4.5 of $HWMId_{tx}$. But very soon the Tropical Rainforest and the Guinea Savannah will be covered by HWs of magnitude 12 (Very extreme) in 2033. Very extreme HWs will encompass the Coastal and the Guinea Savannah from 2048. This will continue increasing spatially toward the Sahel, the West Sahel in 2073 and the East Sahel from 2093. From 2088, the Sahel will experience in average super extreme and ultra extreme HWs while the South will experience normal to severe and finally to extreme HWs.

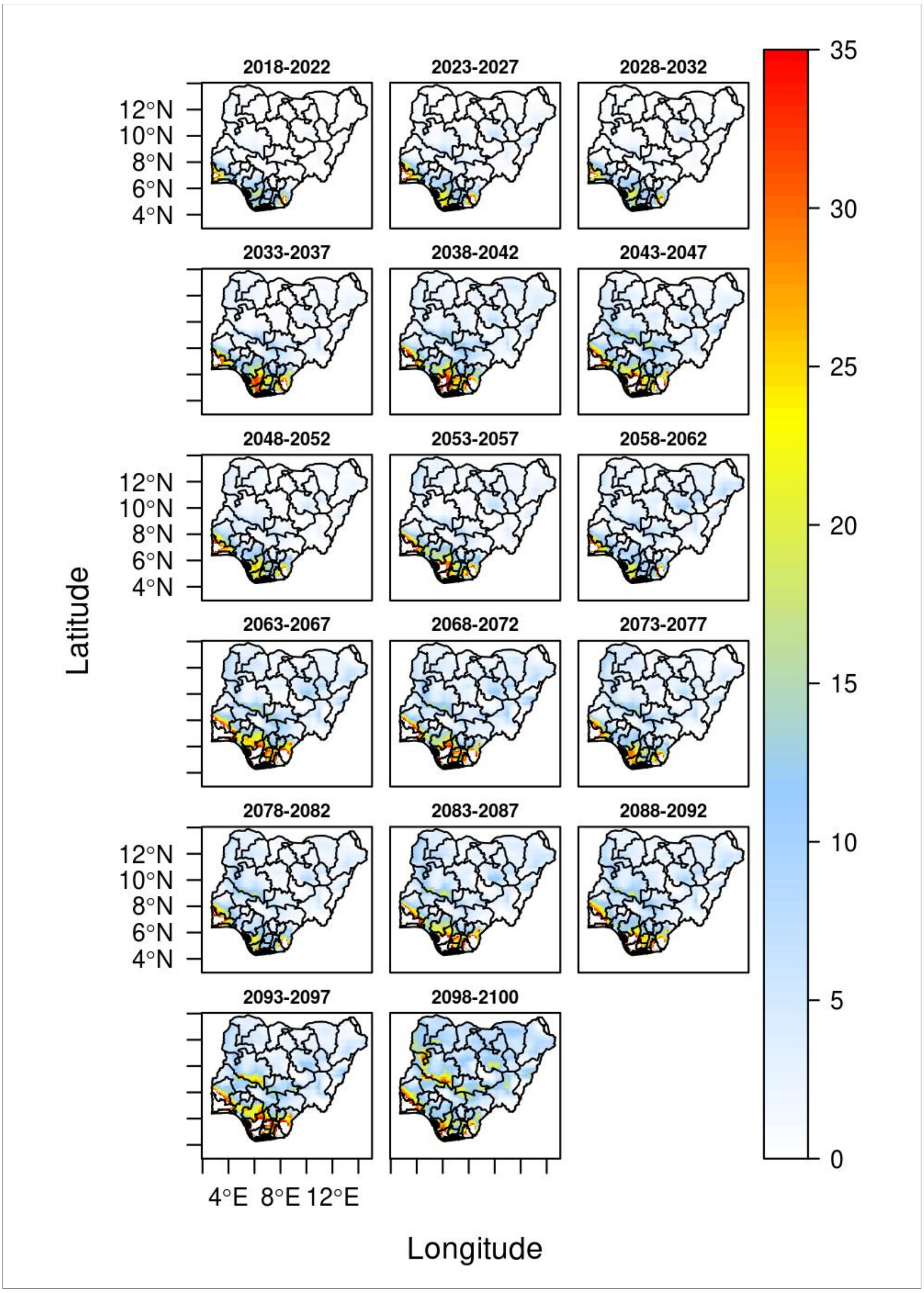

Figure 4.56 Heat Wave Magnitude (HWM) using HWMId on TX ($HWMId_{tx}$) in Nigeria from 1918-2100 under RCP4.5 in 5 years averages

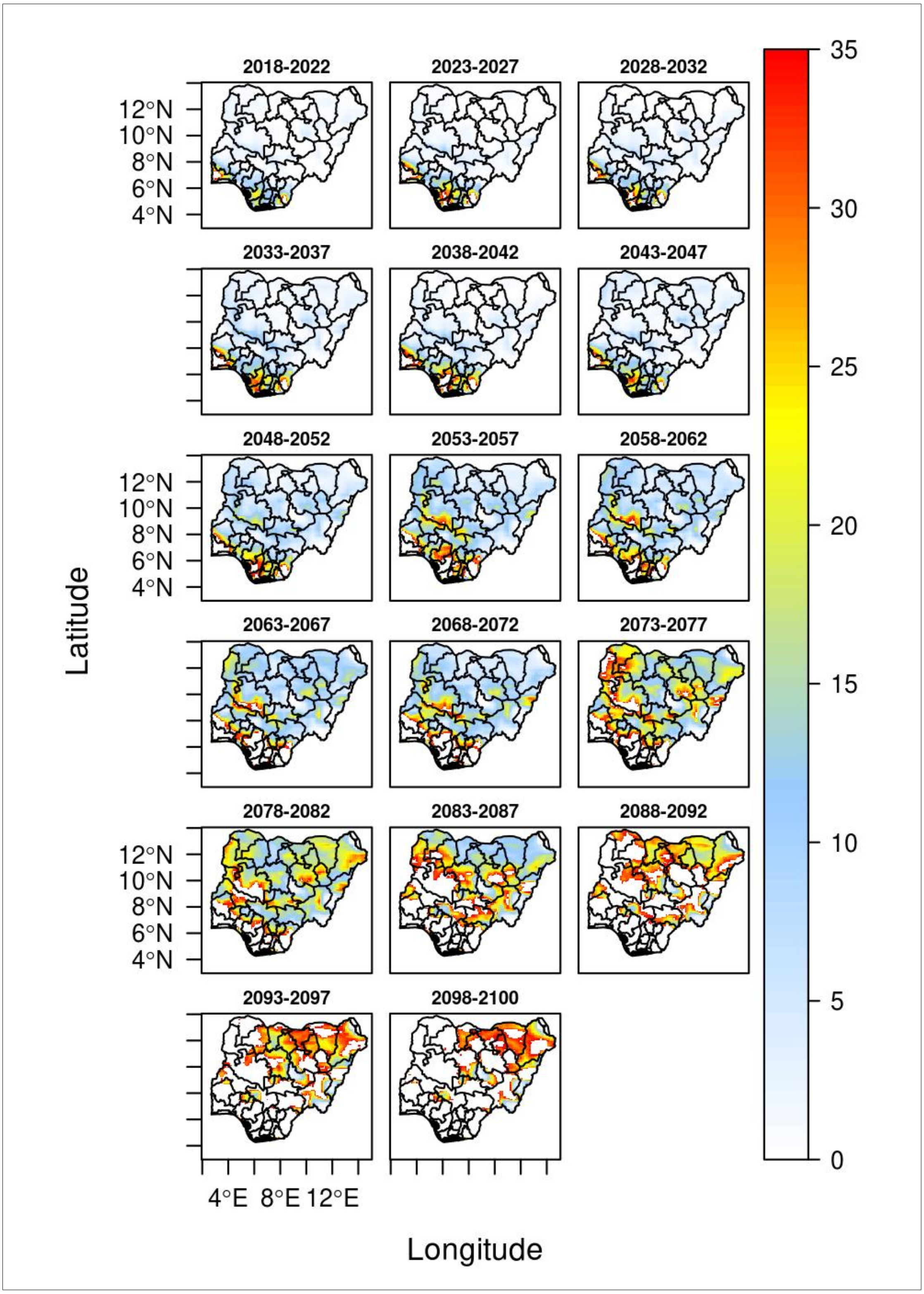

Figure 4.57 Heat Wave Magnitude (HWM) using HWMId on TX ($HWMId_{tx}$) in Nigeria from 1918-2100 under RCP8.5 in 5 years averages

The occurrence of HWs in Nigeria is studied and five (5) characteristics were presented. The results showed a gain in the land area spread over by HWs. The HWM according to the HWMId results will seriously increase from 2050. The results can be compared to the one obtained by Russo *et al.* 2015 when presenting the future HWs under the two scenarios. According to the study, HWs will become normal from 2040 in Africa. Many other studies confirmed that under climate change like (Dosio, 2016; Odoulami *et al.*, 2017). The predicted HWM using the $HWMId_{tn}$ under RCP8.5 will be similar to the European Summer in 2003 from 2058 (in the Coastal zone) in Nigeria.

In comparison to the previous HWs that occurred in Europe and Russia before 2003, from 2058 the HWM will be greater in Nigeria. The European Summer highest HWMId was 24-36 (Russo *et al.*, 2015) while the highest peak for Nigerian $HWMId_{tx}$ will be from 2058 and greater than 35 in many States starting from the Coastal zone. From 2038 under RCP8.5, the $HWMId_{tx}$ will be more severe in the Coastal zone than the Russian 2010 HWs published in *The New York Time, on July 19 2010*, that wilt their crops (Russo *et al.*, 2015).

The HWM using the $HWMId_{tx}$ will be greater than 100 in Cross River, Bayelsa, Ogun and Lagos in 2038. Another serious one will be observed in 2051 that will affect the Coastal zone with greater HWM than 90 and the Guinea Savannah with magnitude greater than 40 in average. This will happen in 2053, 2055, 2057 respectively and become more frequent as on yearly bases from 2061 where the Coastal will suffer higher HWM followed by the Tropical Rainforest the Gunea Savannah and the Sahel where the HWM will be in average greater than 40 (Ultra Extreme HW). In 2074, Niger

State will be the field of high HWM, greater than 100, more intense than the 2010 Russian HW.

4.4 Trends of HWs characteristics

A trend analysis was carried on the different HW aspects and the different definitions (3) used in the study under the two (2) storyline (RCP4.5 and RCP8.5). The hottest nights (TNx) from 1981 to 2100 in Figure 4.58 show a significant trend in almost across the whole country. Mainly the Coastal zone has a p-value < 0.05. Many areas in the Guinea Savannah are not statistically significant. The trend is negative in some places and positive in some other part in the country. For instance the (a) reveals that Borno and Adamawa particularly have a negative slopes (-0.03 °C). The major parts of the Sudan Savannah and Sahel show also negative slopes (-0.01 °C). The general slope is low but the Coastal zone has entirely a positive slope (0.01 °C).

Under RCP8.5 some part of Adamawa, Borno and Plateau have more than 0.05, so not significant, but the rest of the country show a significant trend of TNx. The slope is negative in the extreme North East of Borno State and also in a small part of Adamawa, but the rest of the country have a slope between 0.01 °C and 0.03 °C in Figure 4.59 implying that the there is a decreasing trend of TNx with a possible reduction of the temperature of Tnx in the extreme North East of Borno. The Hottest Nights in general in Nigeria will have a statistically significant trend with a low slope (negative and positive) predicting an increase in the temperature of TNx. The same pattern is observed with the Hottest Days (TXx) under RCP4.5 and RCP8.5.

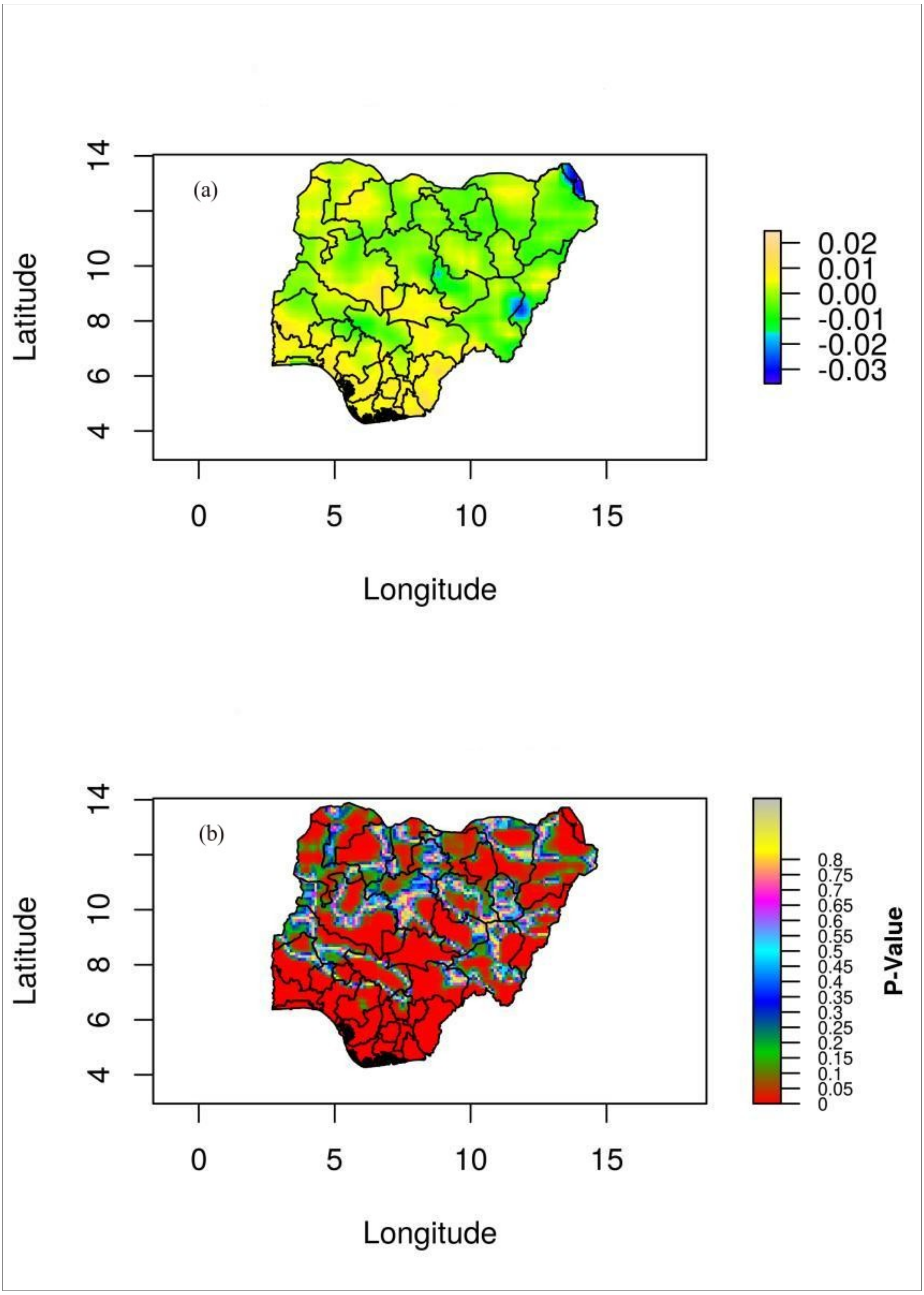

Figure 4.58 Spatio-temporal Trend of Hottest Nights (TNx) under RCP4.5; (a) Slope; (b) P-value

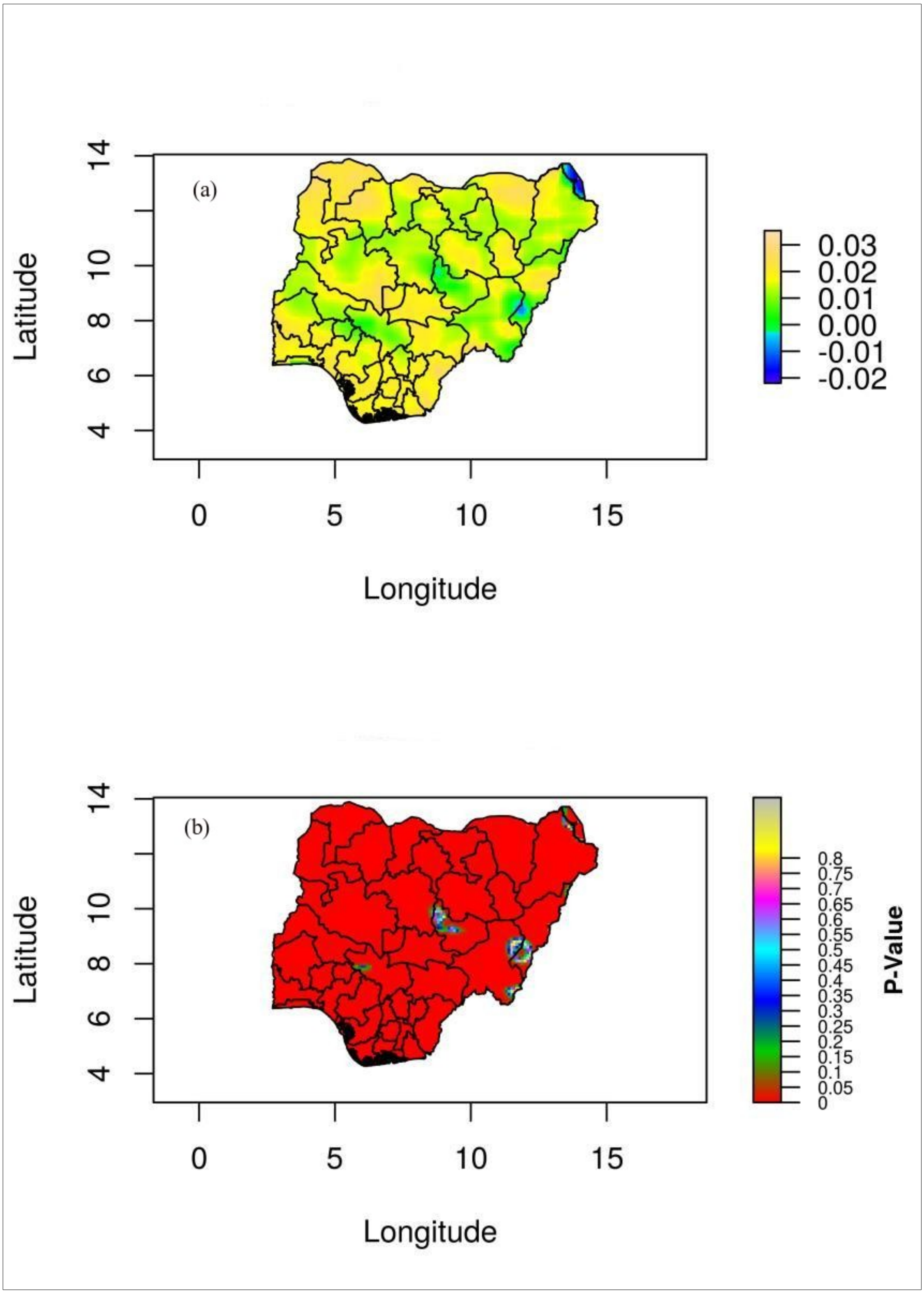

Figure 4.59 Spatio-temporal Trend of Hottest Nights (TNx) under RCP8.5; (a) Slope; (b) P-value

Under RCP4.5 the HWN using TN90 has a significant trend all over the country except for the line in the Figure 4.60 covering the Northern part of the Coastal zone and the East of the Tropical Rainforest. The slope is negatively low in the Coastal zone. The Tropical Rainforest and the Guinea Savannah have between 0.02 and 0.04 event. The two last zones in the North (Sudan Savannah and Sahel) have higher slopes (0.06-0.10 event). The higher the slope the greater the HW event occurrence (increasing or decreasing). The Figure 4.61 shows the trend of HWN for TN90 under RCP8.5. The pattern observed is similar to the one discussed in Figure 4.60.

The trend of HWN for TX90 is not very different under the two scenarios. The slope reaches 0.12 event in the Sudan Savannah and also in the Sahel. The lowest slope values are observed in the Coastal zone. The Tropical Rainforest and the Guinea Savannah HWN for TX90 is between 0.04 and 0.10 events.

The p-value of HWN for EHF is significant especially in the Coastal, the Tropical Rainforest, the Sudan Savannah and the Sahel. The Guinea Savannah has many areas where the p-value is higher than 0.05. For the two storylines (RCP4.5 and RCP8.5), the slope vary from -0.02 and 0.0 event in the Coastal and Tropical Rainforest zones. The Guinea Savannah have a slope from 0.0 to 0.03 event while the Sudan Savannah and the Sahel have from 0.04 to 0.07 event. This imply that the Coastal and Tropical Rainforest zones will have decreasing trends of HW events over time but with very low magnitudes while the other zones will experience an increase in the HWN with more events according the zones. An increase in the number of HW events will impact human, animals and plants health and even the infrastructures.

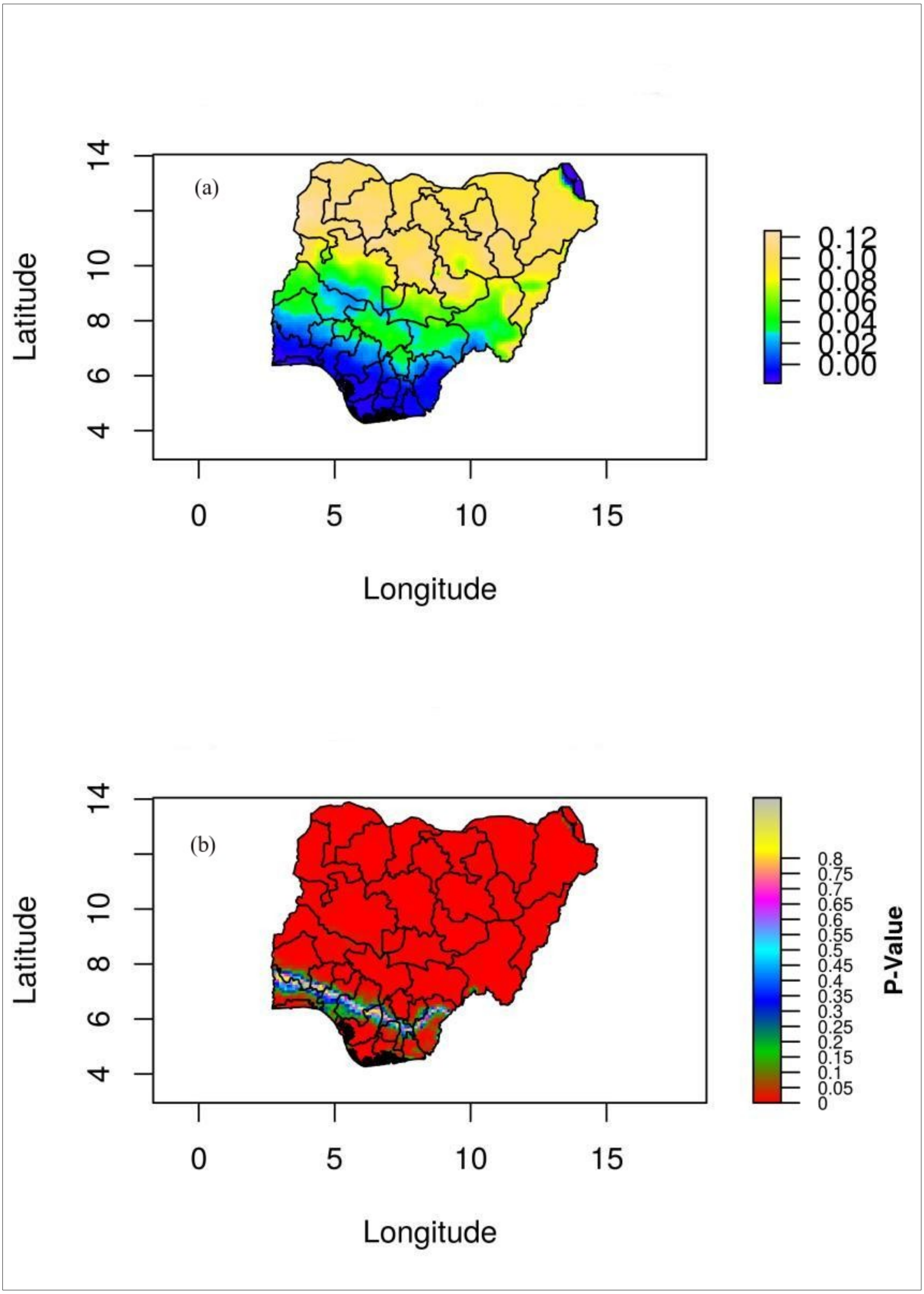

Figure 4.60 Spatio-temporal Trend of Heat Wave Number (HWN) using TX90 under RCP8.5; (a) Slope; (b) P-value

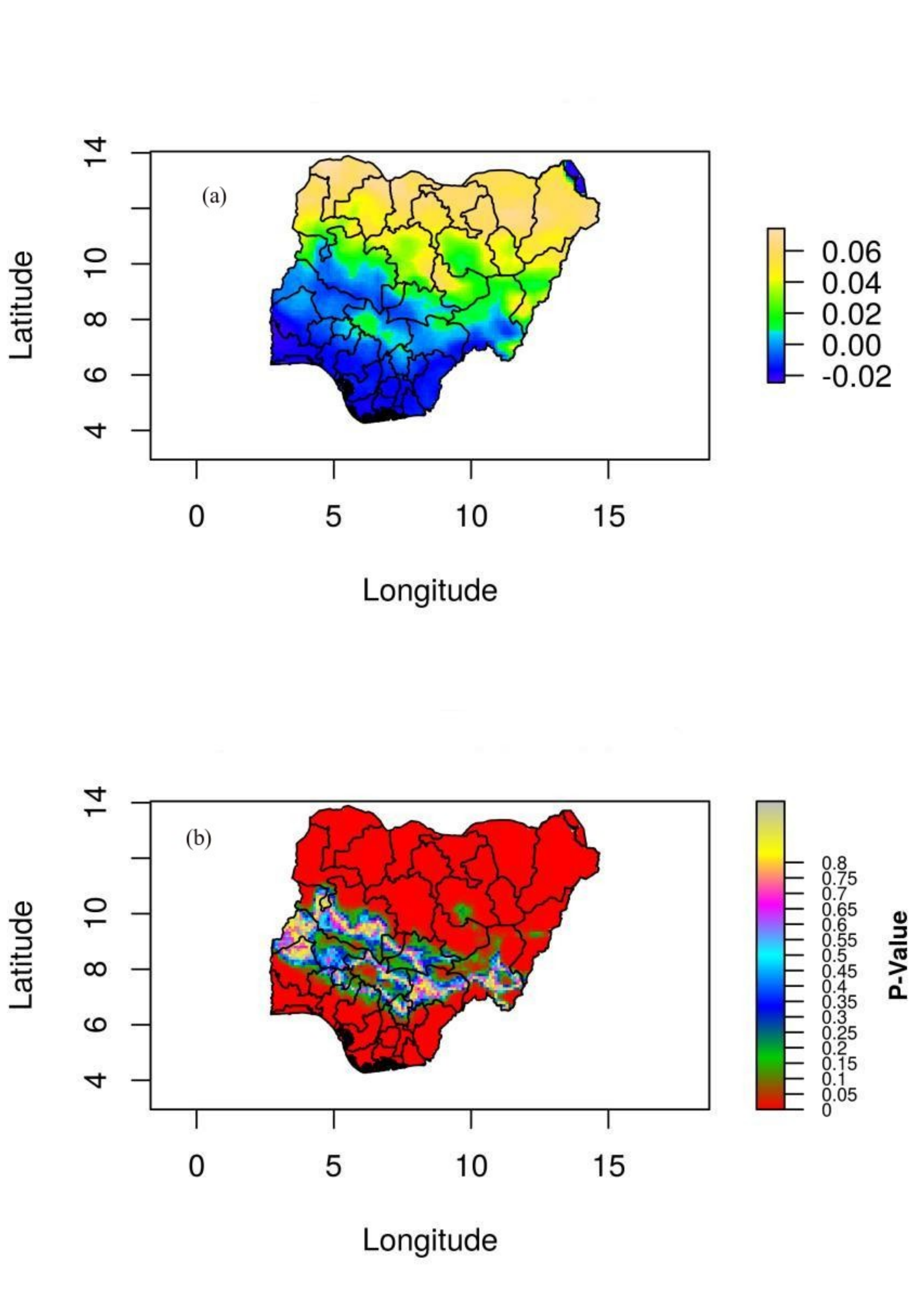

Figure 4.61 Spatio-temporal Trend of Heat Wave Number (HWN) using EHF under RCP8.5; (a) Slope; (b) P-value

The trend of HWD for TX90 is highly positive in Figure 4.62. The p-value is lower than $\alpha = 0.05$ in almost all the country except for some areas in Borno, Cross River and Akwa Ibom States. This means that the HWD for TX90 has a significant trend in almost all the country. The slope is also high from 0 to 4 days. The Sahel, the Sudan Savannah and parts of the Guinea Savannah have 0 to 0.5 days, the Southern part of the Guinea Savannah and the Tropical Rainforest have 1.3 to 1.6 days. The Coastal zone has the highest slope value ranging between 1.5 and 3.5 days. The duration of HWs have been significantly increasing and will continue in the future especially in Lagos, Delta, Bayelsa and Rivers. The pattern discussed is similarly observed under the two scenarios.

With TN90, the HWD p-value is totally significant in all the Nigeria under the two scenarios. The slope is also low in the Sahel and Sudan Savannah (0-1 days) while the Guinea Savannah and the Tropical Rainforest are having 0.5 to 1.8 days. The Coastal zone has the highest values here again (1.5 to 3.2 days).

The HWD for EHF also have a totally significant trend over the time series (1981-2100) except for the Coastal zone where there was no record. Indeed, the slope shows no record for the Coastal zone, but a high slope for the Tropical Rainforest. The Guinea Savannah have from 1.5 to 2.1 as slope in day; there will be an increase in the length of the longest HW. Finally, the lowest records were seen in the Sudan Savannah and the Sahel Figure 4.63. The results are similar in the two scenarios.

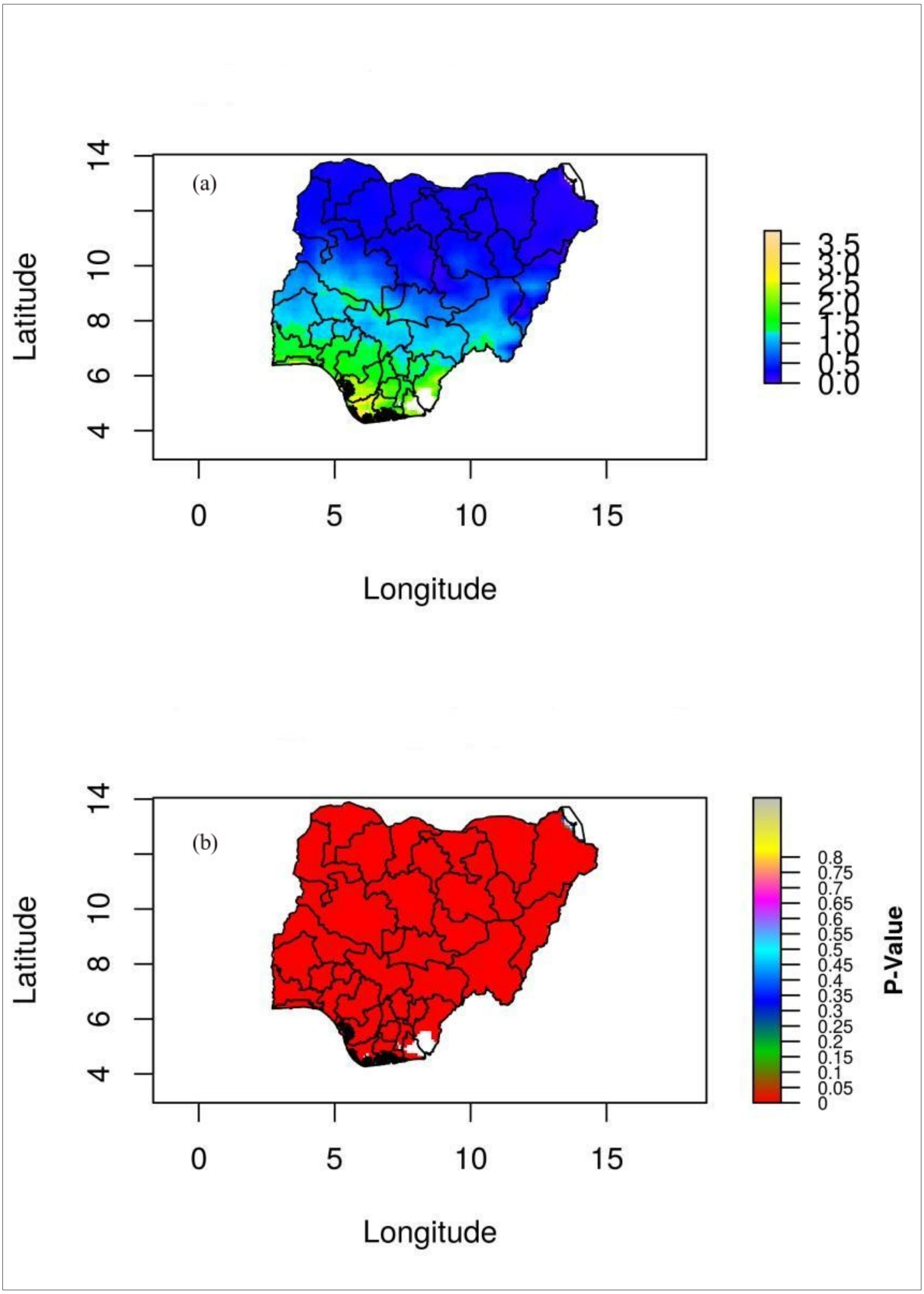

Figure 4.62 Spatio-temporal Trend of Heat Wave Duration (HWD) using TX90 under RCP8.5; (a) Slope; (b) P-value

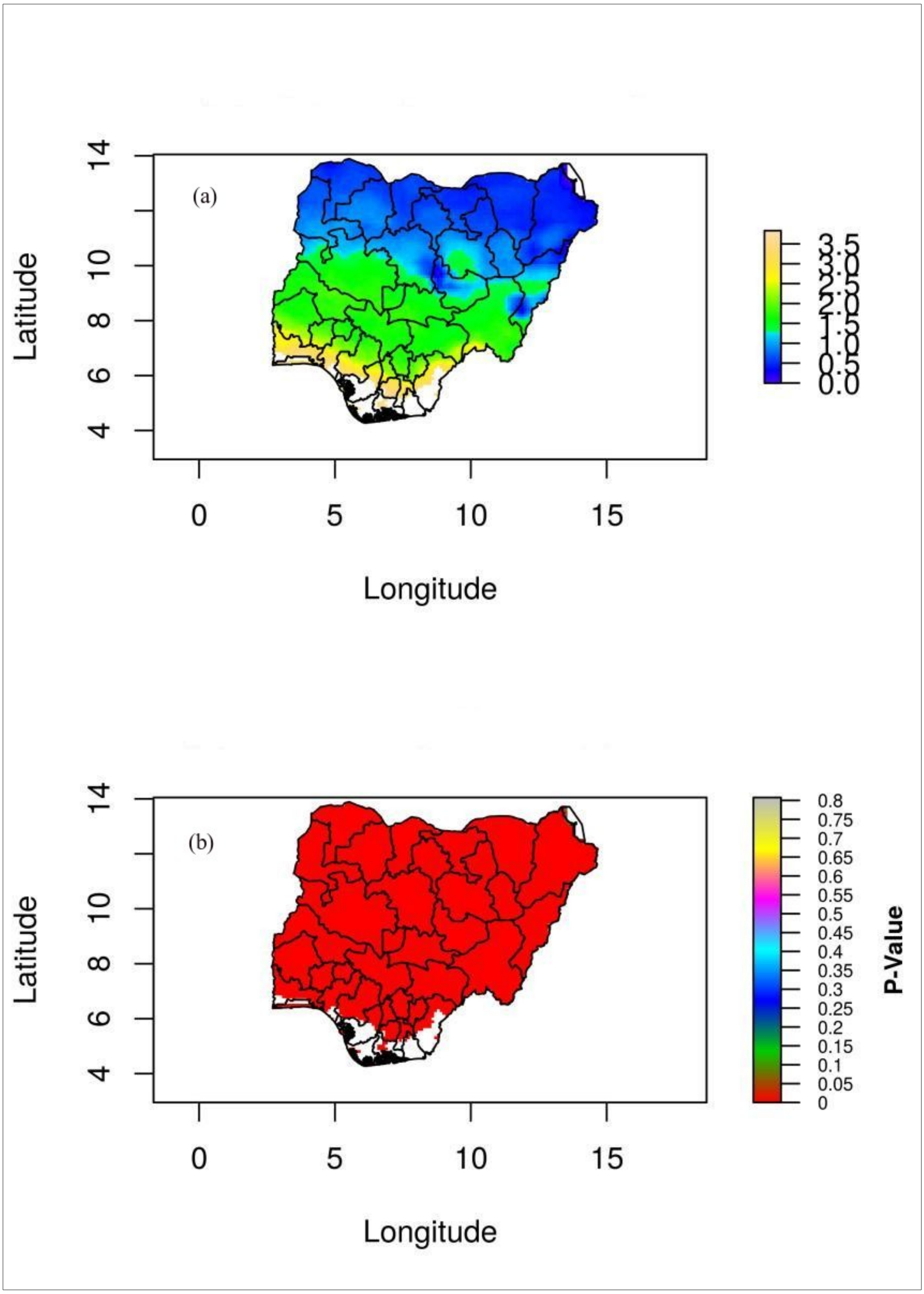

Figure 4.63 Spatio-temporal Trend of Heat Wave Duration (HWD) using EHF under RCP8.5; (a) Slope; (b) P-value

For HWF, the trend was significant in all the zones, but the Coastal zone showed a non significant trend. In the HWF for TN90, the slope is 0 day (no increase in the number of days contributing to an individual heat wave) in the Coastal zone, 0.5 to 1 day in the Tropical rainforest and Sahel, and 1-1.5 days in the Savannah zones. The same pattern was observed with TX90 (Figure 4.64) with a bigger coverage of the non significant area in the Coastal zone. The Western part of the Sudan Savannah and the Sahel had a higher slope than the Eastern part and the Guinea Savannah has the highest slope (1.6 days).

With EHF in Figure 4.65, the pattern was not different except for the non significant trend areas that cover all the Coastal and part of the Tropical Rainforest. The slope was 0 in the Coastal zone, 0.5 day in the Tropical Rainforest and partly in the Guinea Savannah. The Sahel, the Sudan Savannah and the Guinea Savannah carried the highest slope values, 1 to 1.5 days.

The trend of HWA for TX90 is spatially homogeneous compared to the trend of the previous aspects of HW (Figure 4.66). The trend was statistically significant but low in almost all the country. The Coastal zone had the highest values 0.06 °C to 0.11 °C. The rest of the country had an average between 0.02 °C to 0.05 °C. The TN90 shows also the same pattern with a very low slope varying from 0.0 °C to 0.04 °C.

The EHF in Figure 4.67 has a non significant trend in the Coastal zone. The other zones were showing significant trends. But the trends are low varying from 0.0 °C^2 to 0.11 °C^2. There is a lower trend mainly in Borno State and the States in the middle Sahel.

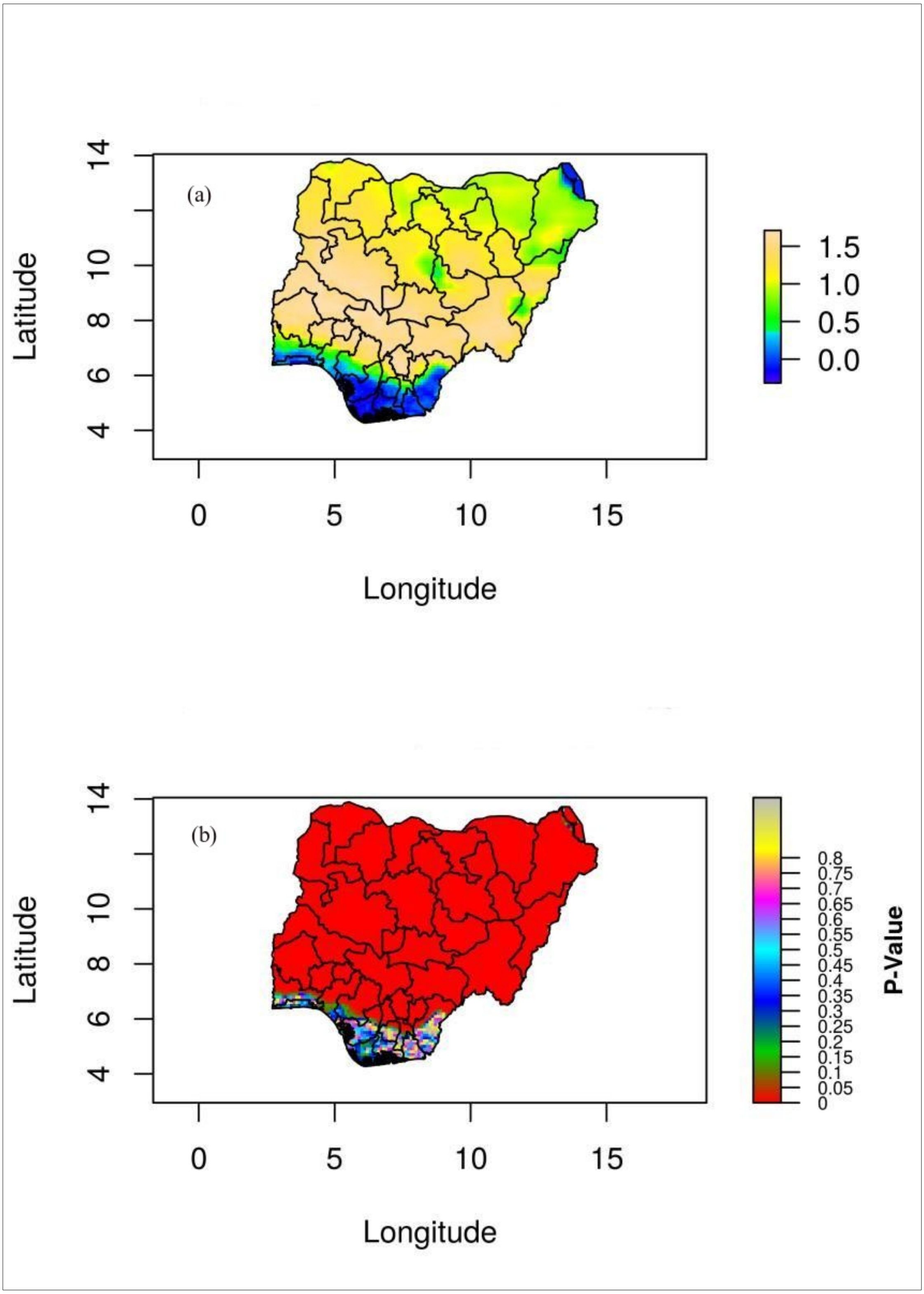

Figure 4.64 Spatio-temporal Trend of Heat Wave frequency (HWF) using TX90 under RCP8.5; (a) Slope; (b) P-value

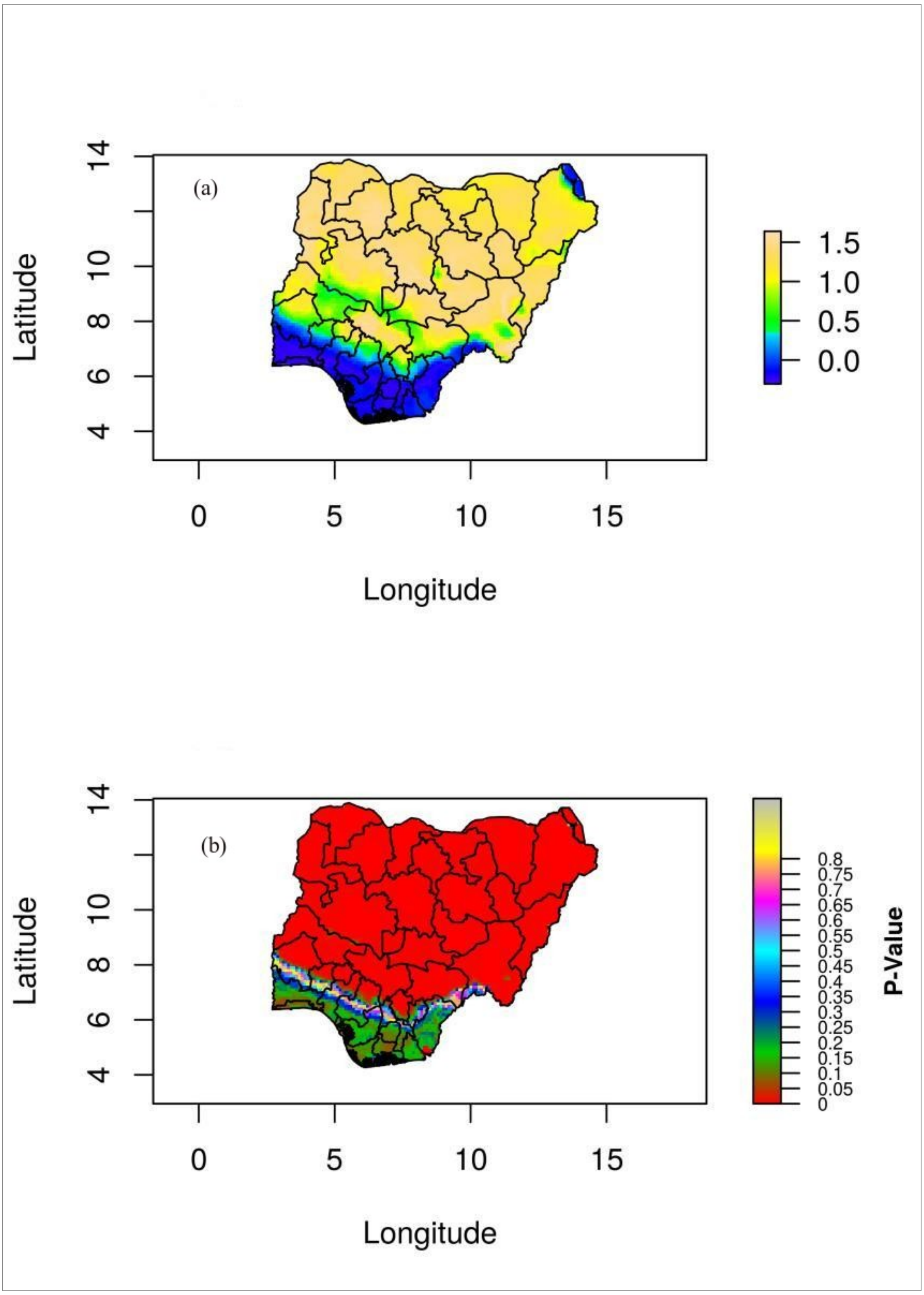

Figure 4.65 Spatio-temporal Trend of Heat Wave frequency (HWF) using EHF under RCP8.5; (a) Slope; (b) P-value

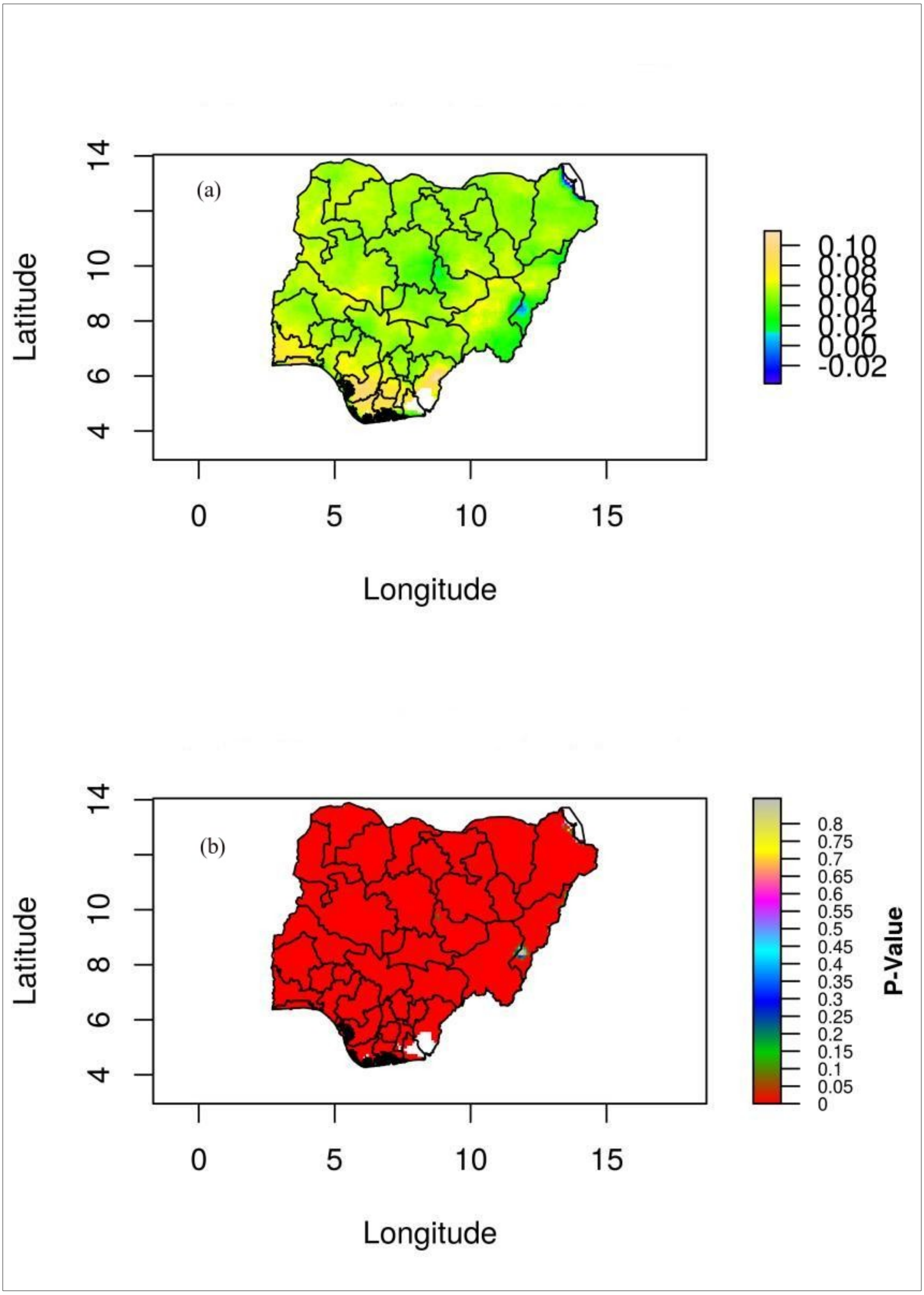

Figure 4.66 Spatio-temporal Trend of Heat Wave Amplitude (HWA) using TX90 under RCP8.5; (a) Slope; (b) P-value

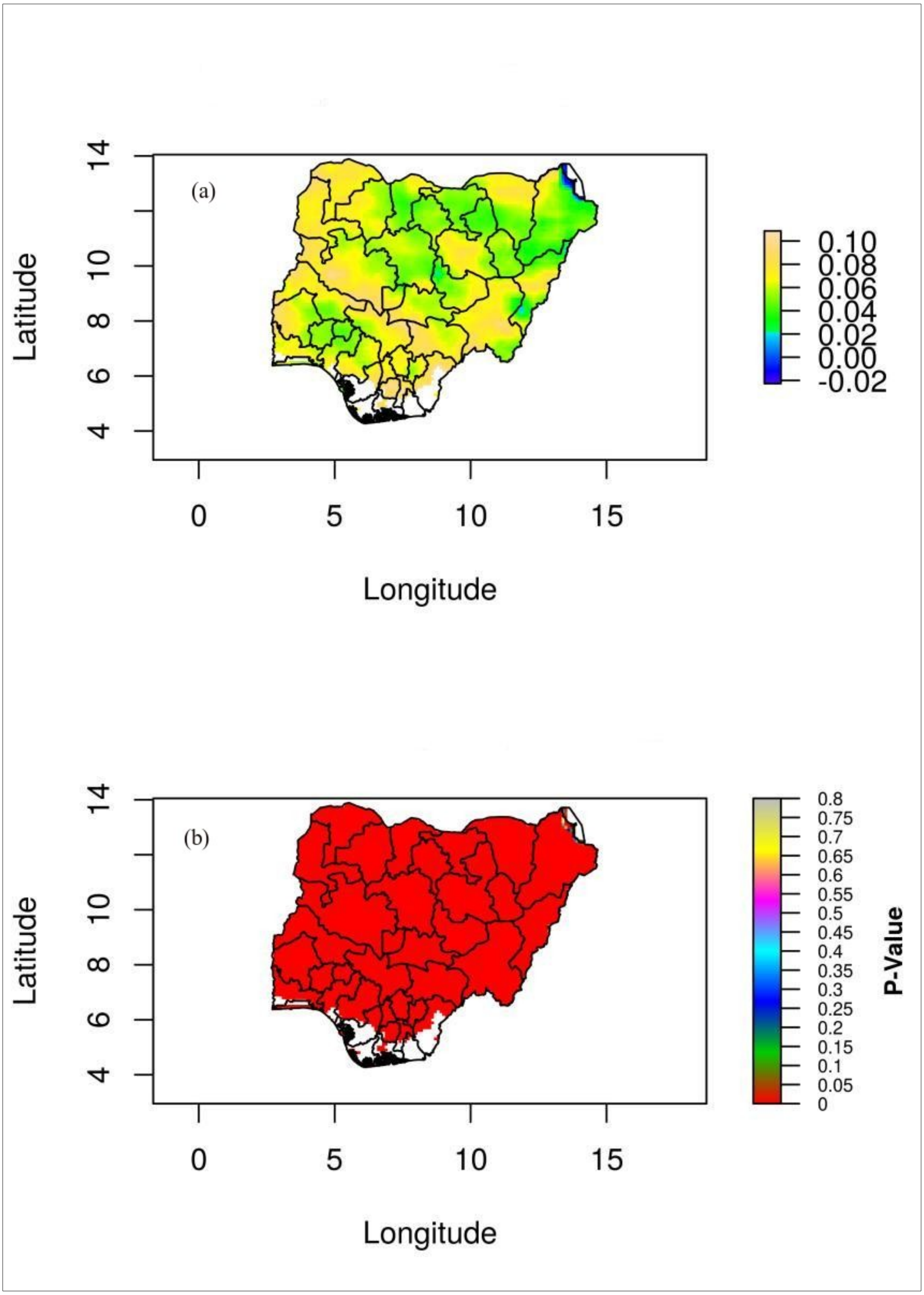

Figure 4.67 Spatio-temporal Trend of Heat Wave Amplitude (HWA) using EHF under RCP8.5; (a) Slope; (b) P-value

The HWM had a significant trend in the country with TX90 except for some area in the East like the South of Borno State, in Adamawa and also in parts of Kaduna and Plateau State (Figure 4.68). The slope vary from -0.02 °C to 0.08 °C and from the North to the South the slope increases. The South had a p-value of 0.08, while the Sahel, Sudan Savannah and parts of Guinea Savannah have 0.02 °C to 0.04 °C.

With TN90, the Northern part of the country, the Sahel and the Sudan Savannah had a non significant trend in the major part giving 0 °C as slope in those areas. But the Coastal zone and the Tropical Rainforest had 0.02 °C as slope. The Guinea Savannah had the highest slope in an overall view (0.03 °C).

With EHF, there was no trend in the Coastal zone, but all the other zones have a significant trend with very low slope. The highest slope, 0.03 $°C^2$ was observed in the Tropical Rainforest and some areas in the Guinea Savannah as shown in Figure 4.69. The general slope of the Guinea Savannah was 0.01 $°C^2$ with the Sudan Savannah, the Sahel and the Tropical Rainforest. This show an increase in the HWM in almost the whole country with the exception of the Coastal zone.

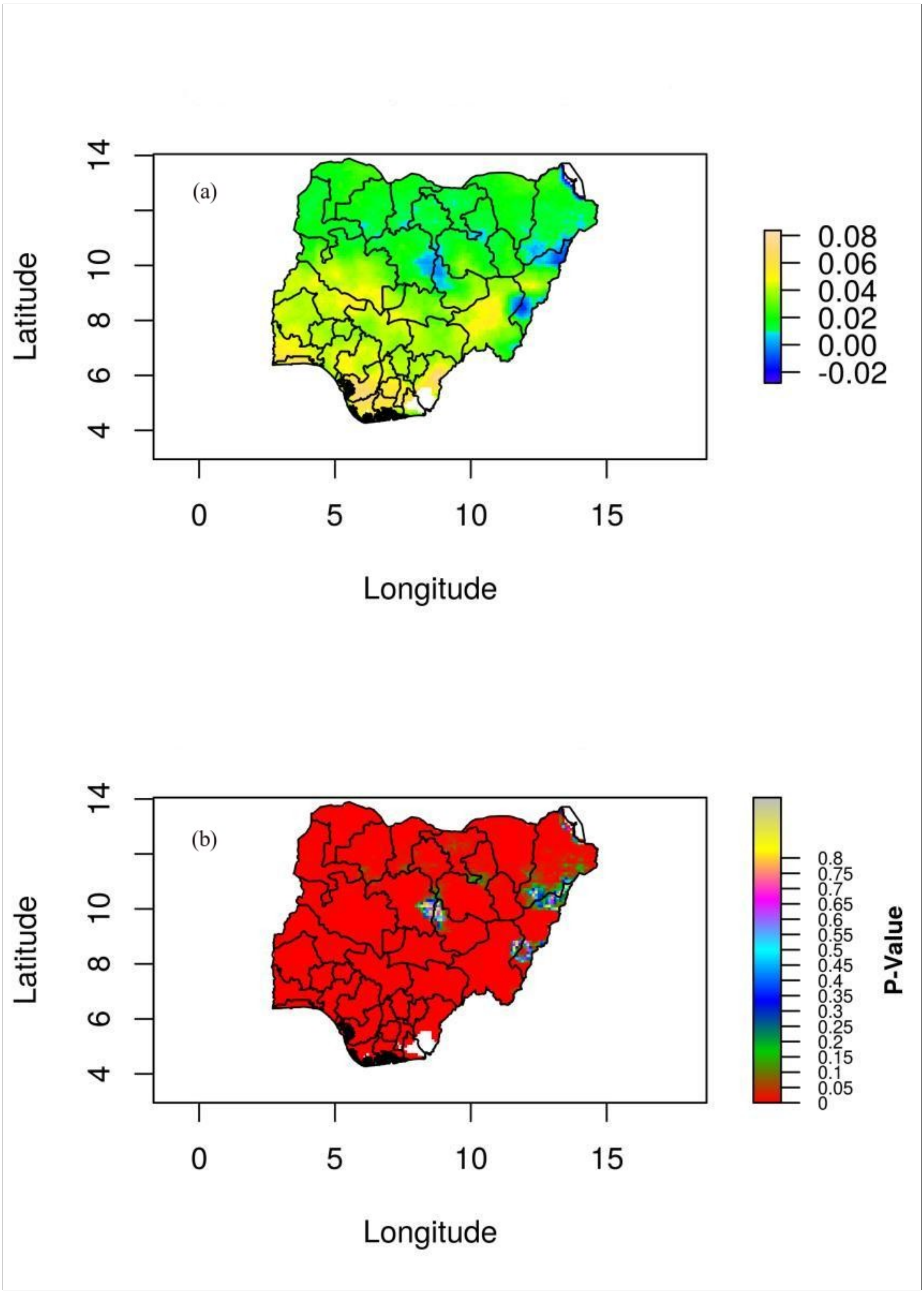

Figure 4.68 Spatio-temporal Trend of Heat Wave Magnitude (HWM) using TX90 under RCP8.5; (a) Slope; (b) P-value

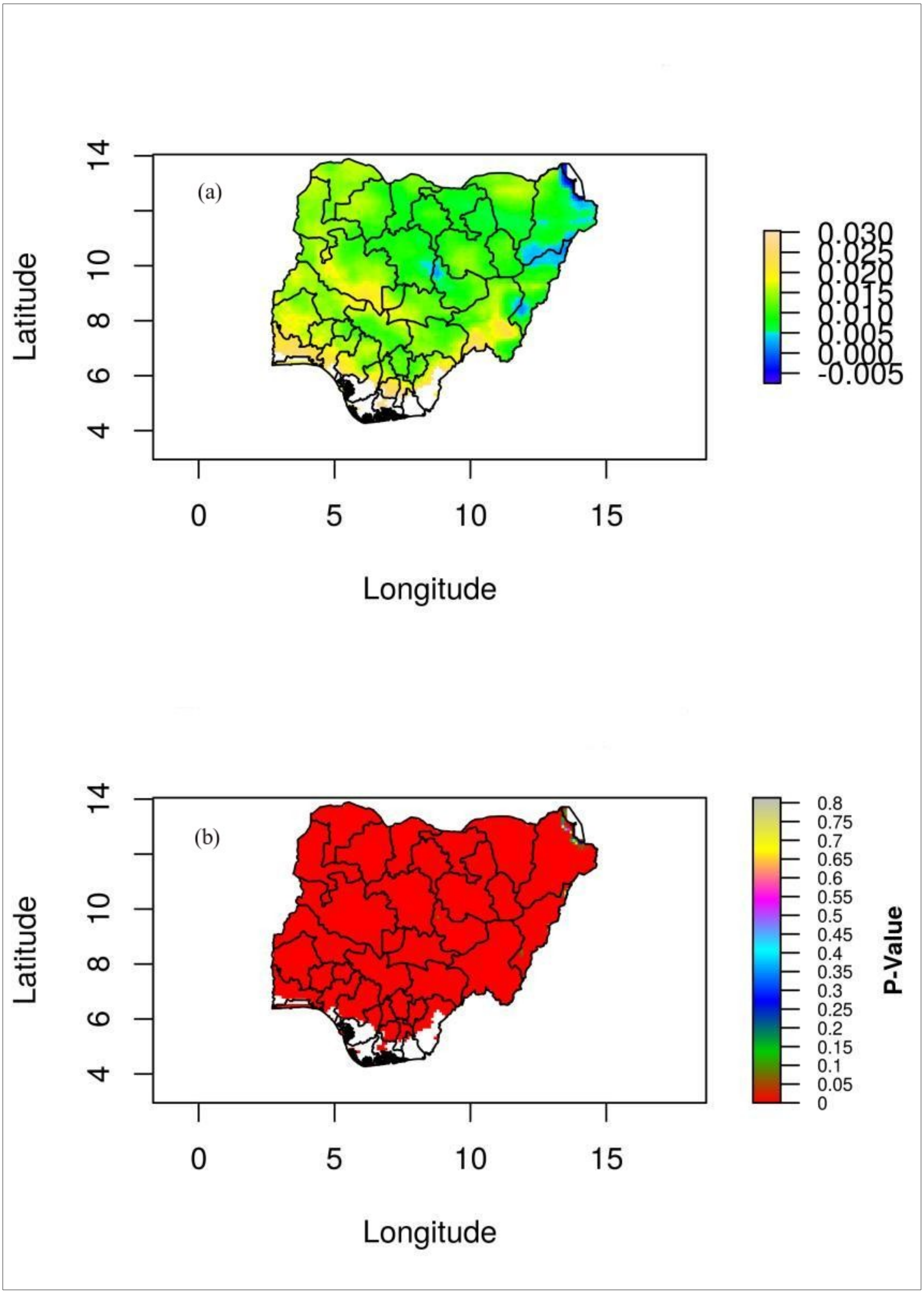

Figure 4.69 Spatio-temporal Trend of Heat Wave Magnitude (HWM) using EHF under RCP8.5; (a) Slope; (b) P-value

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

This chapter concludes the research work and gives recommendations. The overriding purpose of the research was to study Heat Wave (HW) characteristics in the present and future time in different climatic zones of Nigeria. The conclusion and the recommendations were given according to the results of the different objectives. The chapter was divided into two sections. The first one, 5.1 brings the work to a conclusion and the section 5.2 presents recommendations pertaining to the results of the current work.

5.1 Conclusion

Nigeria covers 5 different climatic zones in West Africa. The different zones are agriculture based. Climate change aggravated conditions, led to an increase of the surface air temperature that opens door to extreme events such as drought and HWs. The latter can be dreadful not only to crops but also to animals, human being and infrastructures.

It is paramount to determine the different characteristics of HWs and their occurrence to be able to prepare adaptation measures. The ~ 11 km ERA-INTERIM data was used to detect the spatial coverage and occurrence of HW characteristics in the present time with three definitions, the 90th percentile of daily maximum temperature (TX), TX90, the 90th percentile of daily minimum temperature (TN), TN90 and the Excess Heat Factor (EHF), all based on temperature records. It has been shown that HWs occurred in Nigeria during the 1980s and increased in the 21st century. The HWN effectively increased in the last two decades for the three definitions used with 15 events with TX and TN, and 13 events for EHF. The Duration (HWD) similarly increased in all the country. The Frequency (HWF) has increased during the last two decades mainly with EHF that shown 100 days. The Amplitude (HWA) of HWs had significantly increased in aerial coverage but the records were maintained at 45 °C (TX90), 32 °C (TN90) and from 8 $°C^2$ to 10° C^2 for EHF. The Magnitude (HWM) that is an important measure of HW revealed also a very slight increase with all the definitions, but the EHF showed an increase in the coverage. The Heat Wave Magnitude Index daily (HWMId) was computed and compared to the other indices mainly the EHF where the HWMId showed a different pattern. There was no perceptible increase in the magnitudes and the aerial coverage on maximum temperature ($HWMId_{tx}$) but an increase was observed both in the magnitudes and the aerial coverage of the HWs and on the minimum temperature ($HWMId_{tn}$).

The ~ 44 km CORDEX-AFRICA spatial resolution output of Weather Research and Forecasting Model (WRF) have been interpolated to ~11 km on Nigeria to detect future HW characteristics and occurrences under the two Intergovernmental Panel on Climate Change (IPCC) scenarios, RCP4.5 and RCP8.5. Under the two scenarios, the HWN with TX90 will increase to 17 events/year during 2048-2058, but the aerial coverage will be higher under the pessimistic scenario (RCP8.5). The EHF showed also 12 events with the two scenarios. The HWD will increase to 170 days for the three definitions under the two scenarios. The coverage will still be higher with RCP8.5 with the South of the country as target of long HW events. The HWF will have also 170 days for the three definitions and under the realistic and pessimistic scenarios. But the high frequencies will affect more the Southern part of the country, under RCP8.5 the whole country will experience it from 2060s-2070s. The Amplitude of HWs will increase as well touching more the Sahel throughout the century with 47 °C and 46 °C under RCP8.5 and RCP4.5 respectively for TX90. The TN90 is obviously lower and the EHF shows 17 $°C^2$ and 10 $°C^2$ with very different coverage. The Magnitude of HWs will also increase in the whole country to 42 °C under RCP8.5 whith TX90. HWM will remain 4 $°C^2$ with EHF under RCP8.5 with a greater coverage. Compared to the HWMId, the $HWMId_{tn}$ showed an average of 5 to more than 15, extreme to super extreme HWs under RCP4.5, while RCP8.5 showed from 2048 very extreme HWs in the Coastal and Tropical Savannah and Ultra extreme HWs (>32) from 2073. The $HWMId_{tx}$ showed great increase from 2018 in the Coastal zone where super extreme HWs are likely to occur in Ogun, Lagos and Cross River States among others.

The trend analysis carried on each of the characteristic from 1981-2100 revealed a significant trend $\alpha \leq 0.05$ for all the HW characteristics under the two scenarios except for some highlighted areas in the Guinea Savannah for HWN EHF under RCP8.5, the Sahel and Guinea Savannah for HWM TN90. The slope will vary from negative 0.03 to positive 3.5 with different implications in the different characteristics.

5.2 Recommendations

According to the findings of the study, recommendations can be suggested on the methodology, the occurrence of HWs and their characteristics and also the climate scenarios.

It is an evidence in the present work that the temperature increased and will increase. It is recommended to use assimilated data using observation and reanalysis data for such a study. And researchers can use mean temperature also for the subsequent research using HWMId at a regional high resolution scale. A comparison can be done between drought periods and HWs occurrence to detect possible relationships. Also, looking at the different impacts that HWs may have, it is recommended to conduct further researches on the sectoral impacts of HWs in Nigeria making an emphasis on the HW characteristics on crops and animal production, given that the country is agricultural based. The Health domain also is paramount given that the EHF is a good indicator of morbidity and mortality and the HWMId was compared to the top rated European HWs that caused many human losses.

The pessimistic scenario (RCP8.5) showed dreadful conditions of HW characteristics. Planting trees can be of high importance, either used as adaptive strategy during hot days and intense HWs or a mitigation to climate change in the Coastal area as well as the Sahel. The pessimistic scenario should be avoided. Cities can incorporate heat reduction strategies as cooling systems such as green roof where the roof is covered with grass or plant or cool roofs where the roof is surfaced with reflective materials like the white paint and cooling aggregate paved surface; this will increase the albedo of the cities reducing the Urban Heat Island (UHI) and the intensity/severity of HWs. Such measures help to bring down impacts on public health and urban systems from extreme heat events. Forecasting is an adaptation. The prediction can lead the way to the forecasting of HWs to develop early warning and communication systems. Awareness is also an adaptation system; because many people like farmers are still unaware of HWs that are happening and the ones that are coming. Awareness campaign could be an adaptive strategy for policy makers. Knowing the future occurrence of HWs is an advantage for farmers and policy makers to think about renewable energy to reduce the high dependence on hydro-energy that is an actual issue in Nigeria leading to the excessive use of “generator”. Encourage energy conservation to reduce demand on electricity systems.

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APPENDICES

Appendix A: Trend plots of the different observation station

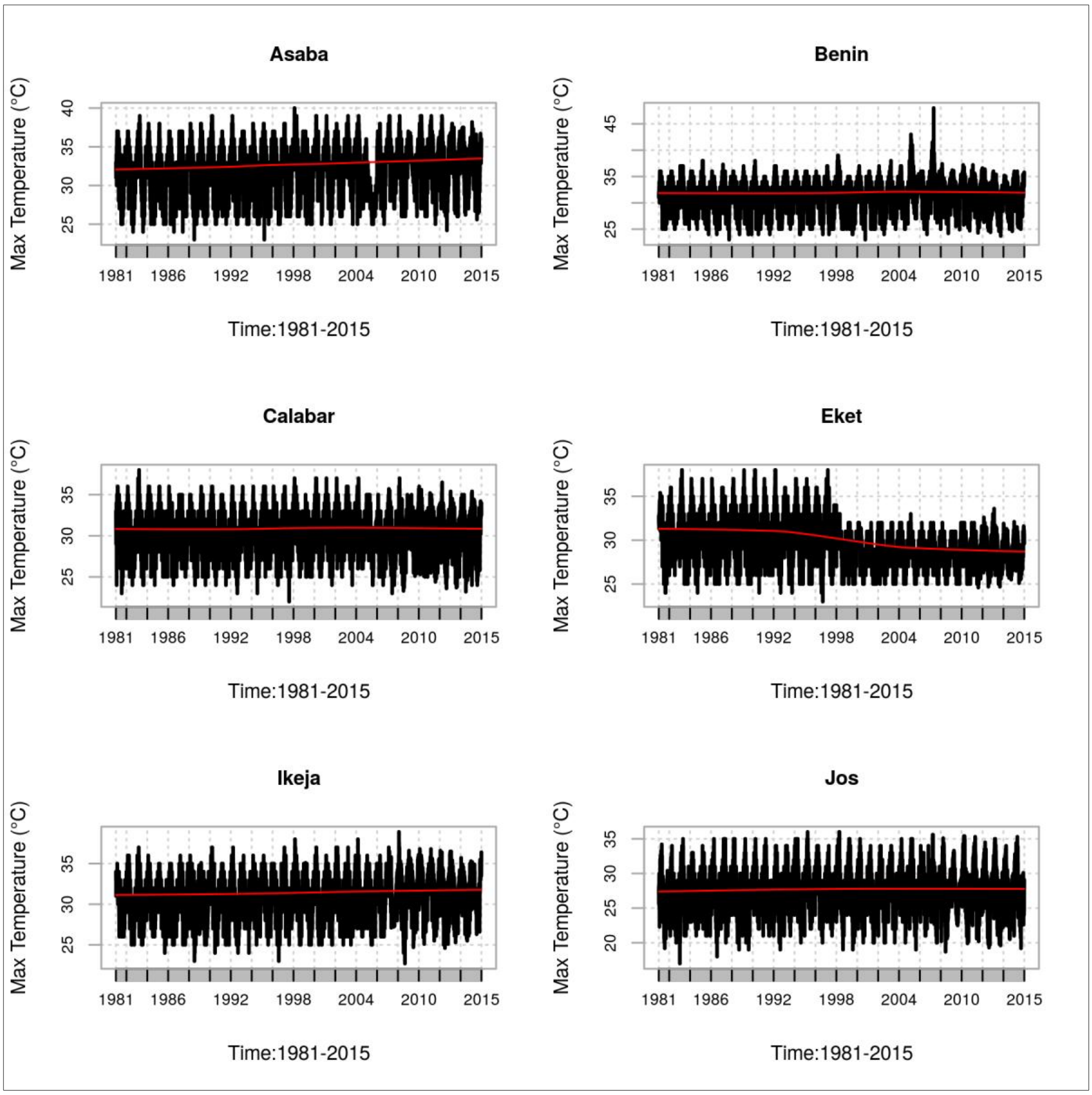


Figure 1 Trend of observed maximum temperature of Asaba, Benin, Calabar, Eket, Ikeja and Jos stations

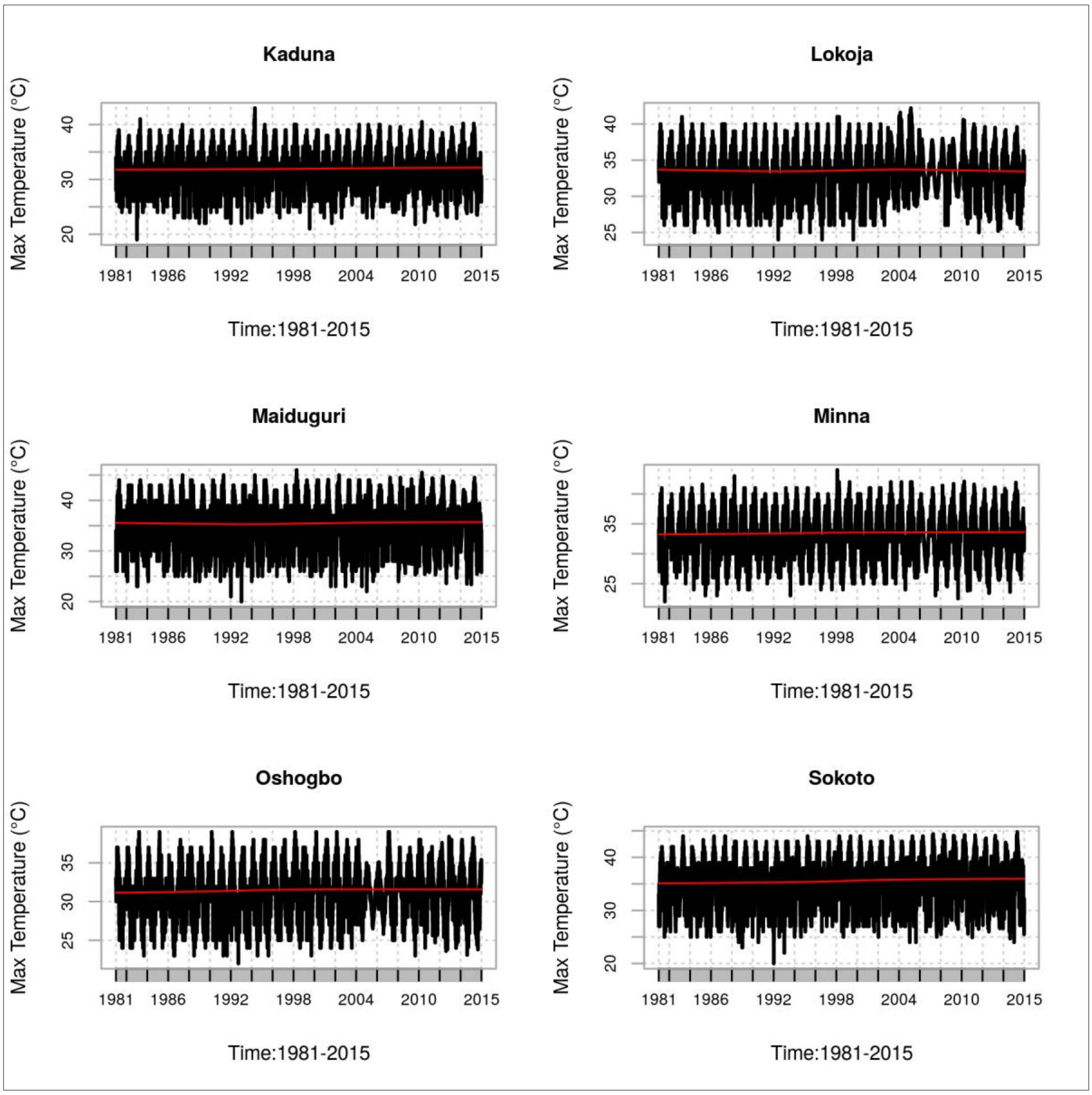


Figure 2 Trend of observed maximum temperature of Kaduna, Lokoja, Maidugri, Minna, Oshogbo and Sokoto stations

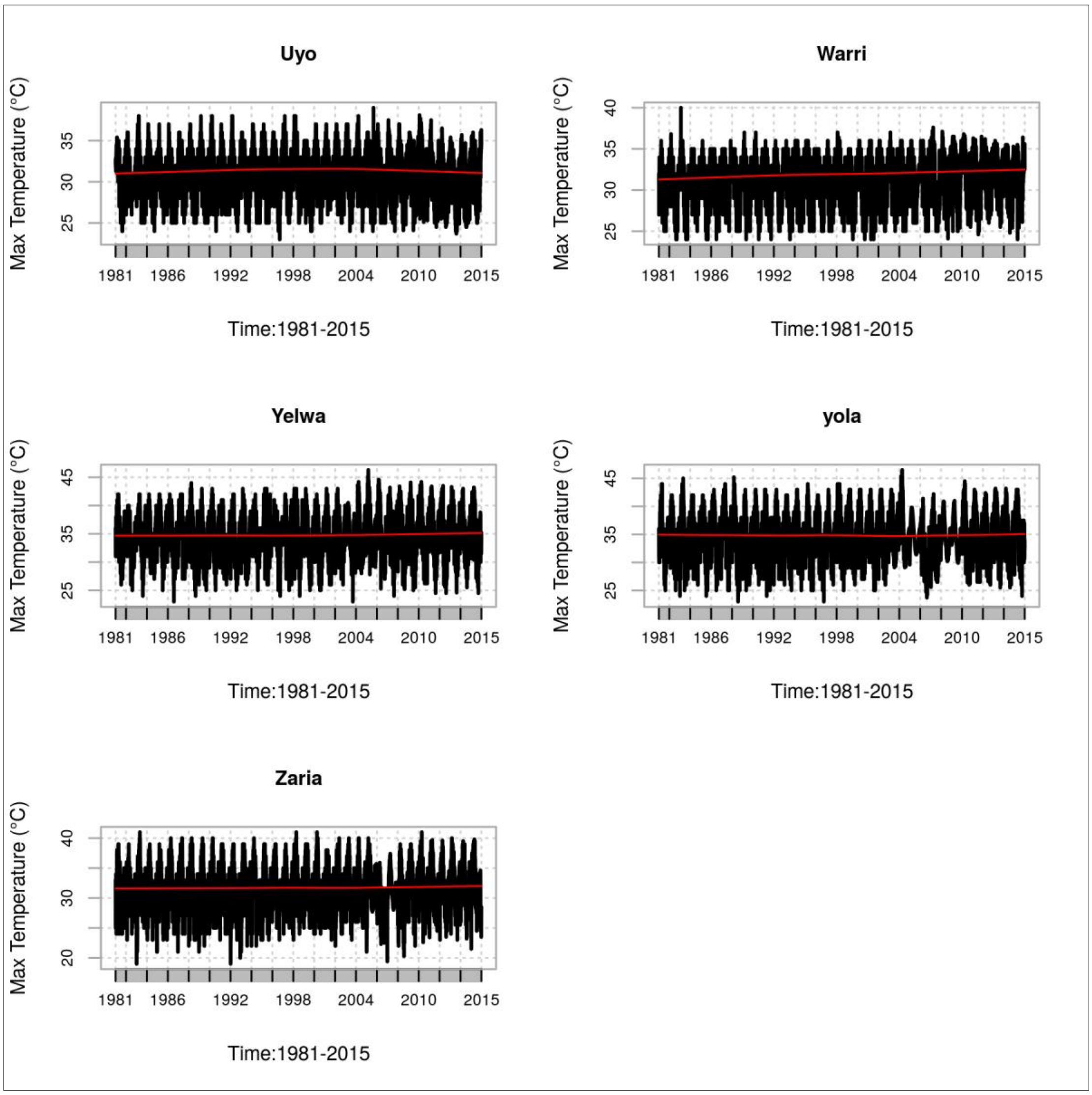


Figure 3 Trend of observed maximum temperature of Uyo, Warri, Yelwa, Yola and Zaria stations

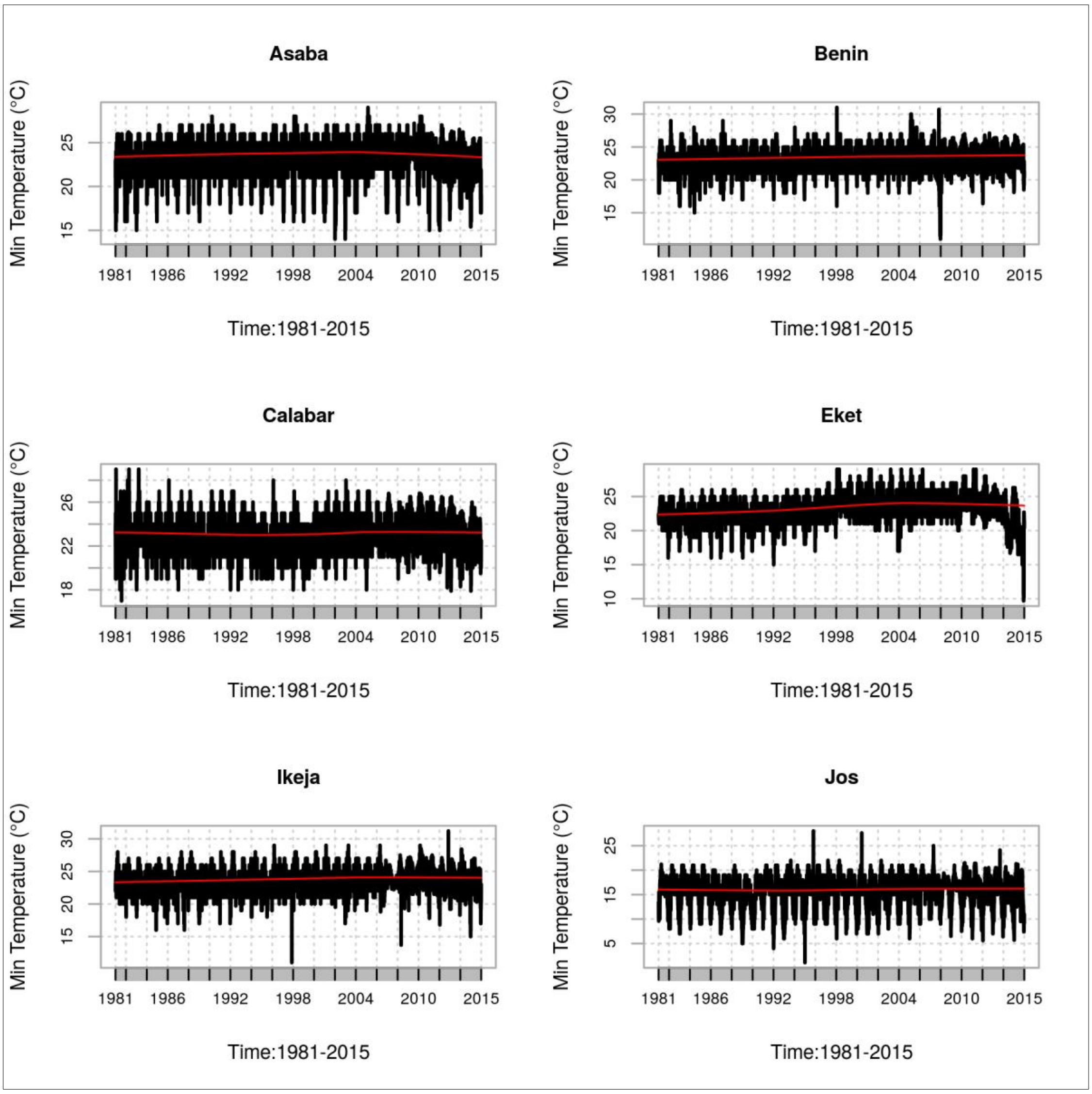


Figure 4 Trend of observed minimum temperature of Asaba, Benin, Calabar, Eket, Ikeja and Jos stations

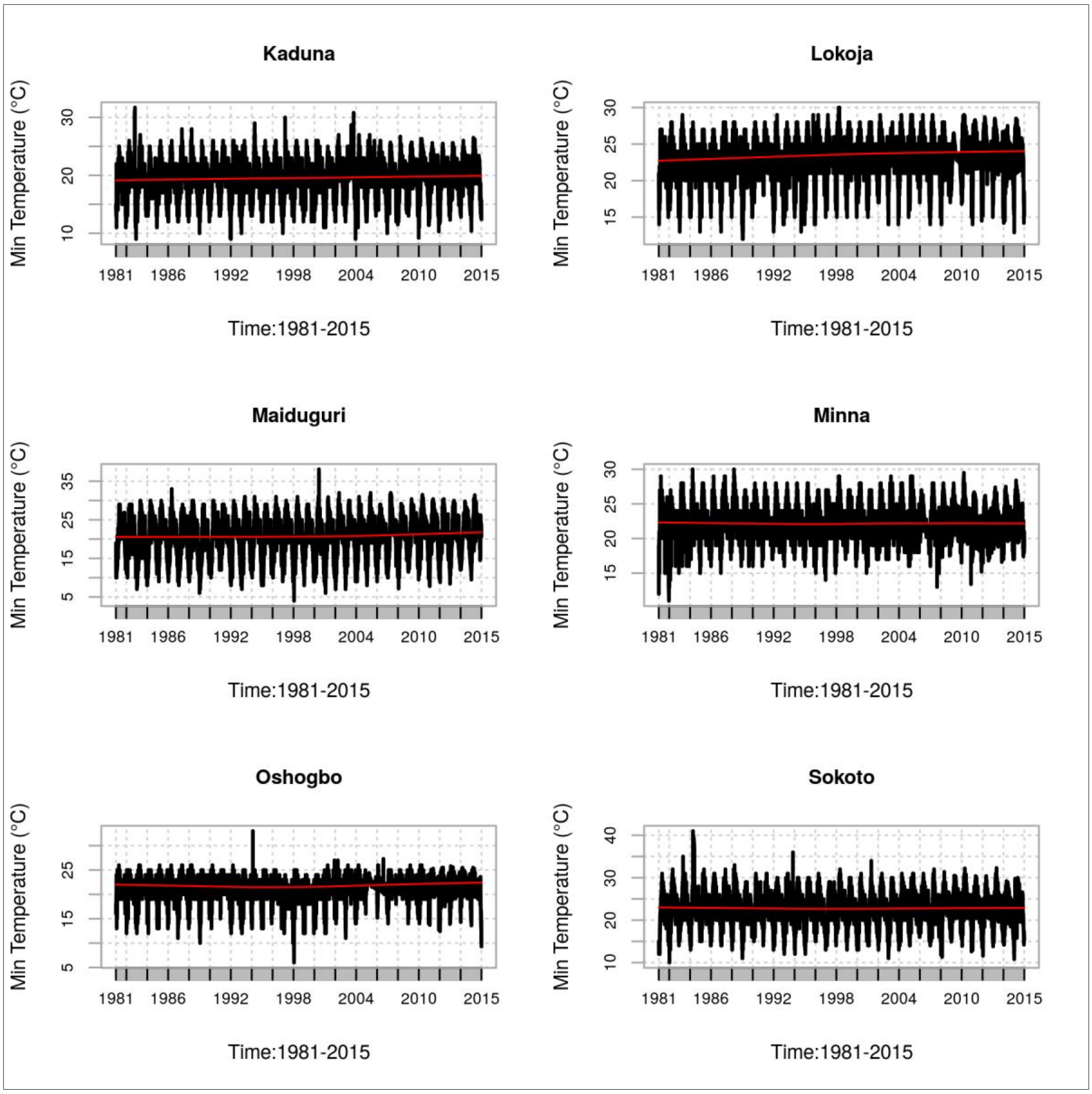


Figure 5 Trend of observed minimum temperature of Kaduna, Lokoja, Maidugri, Minna, Oshogbo and Sokoto stations

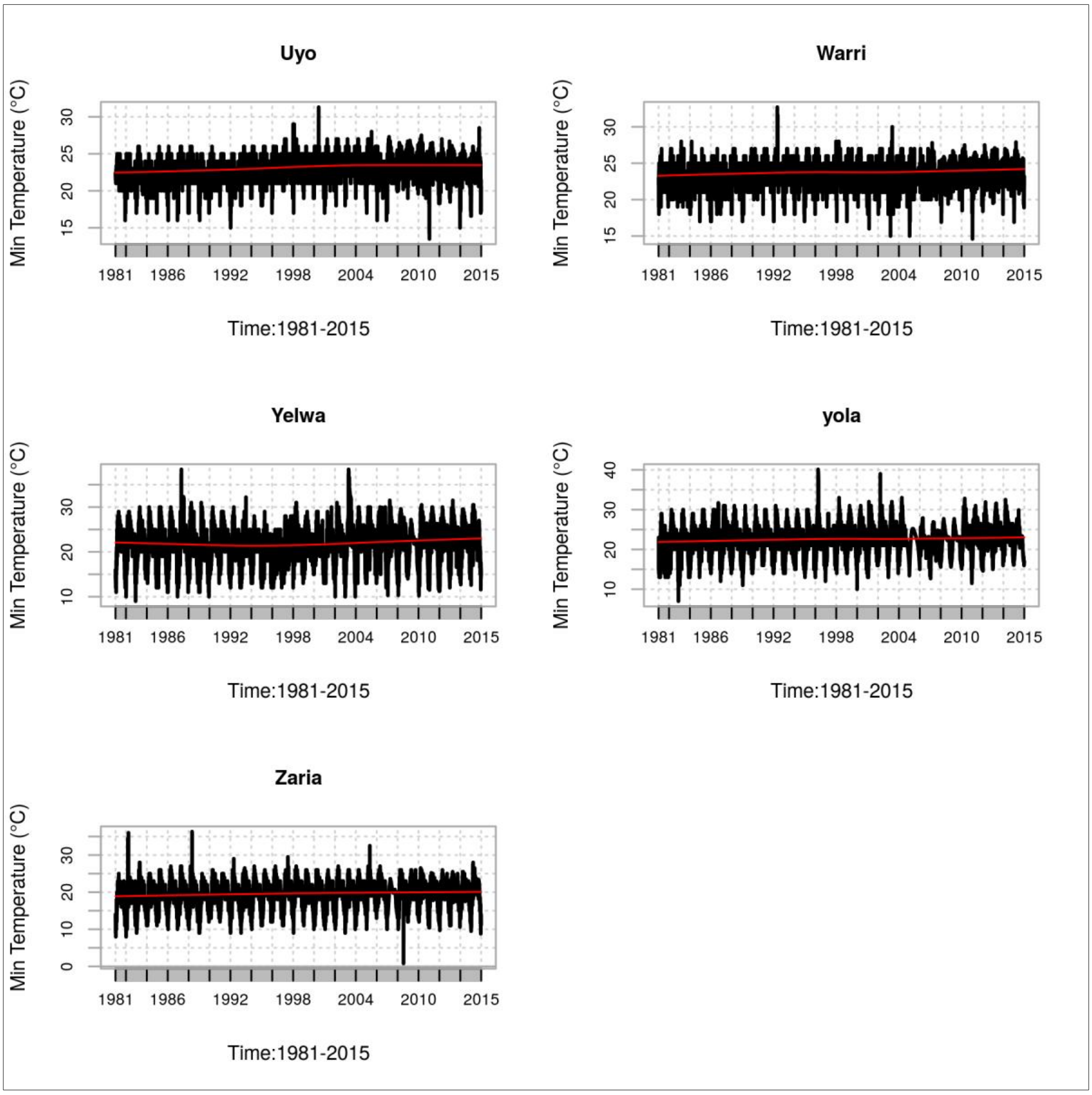
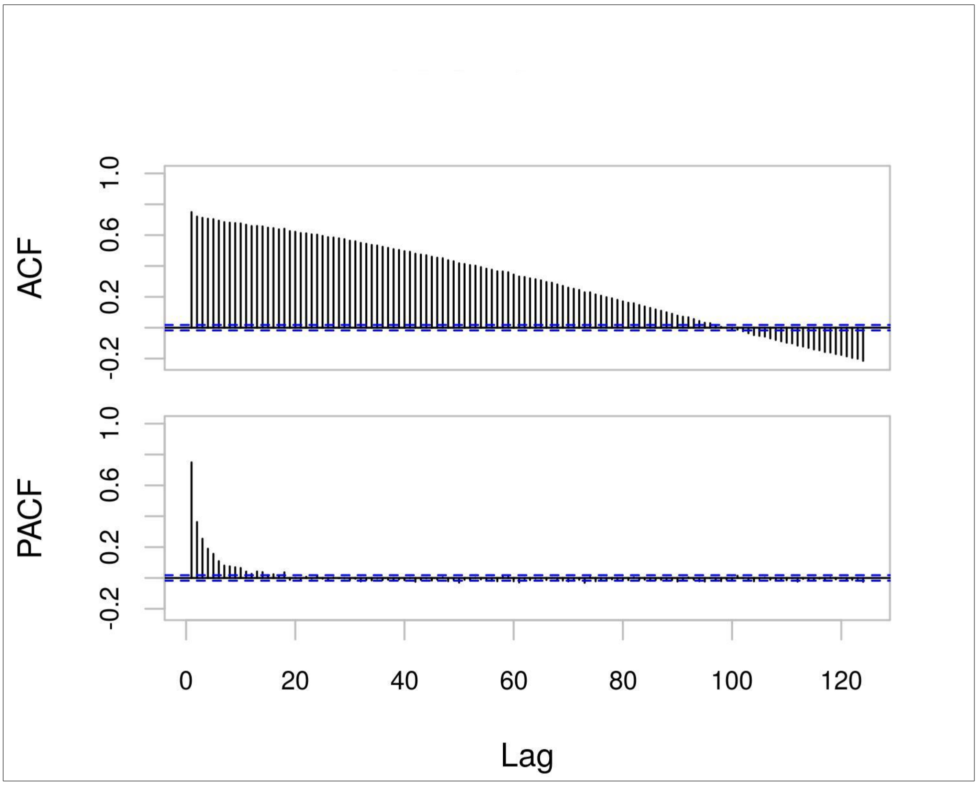


Figure 6 Trend of observed minimum temperature of Uyo, Warri, Yelwa, Yola and Zaria stations

Appendix B: Plots of Autocorrelation (ACF) and partial autocorrelation (PACF)



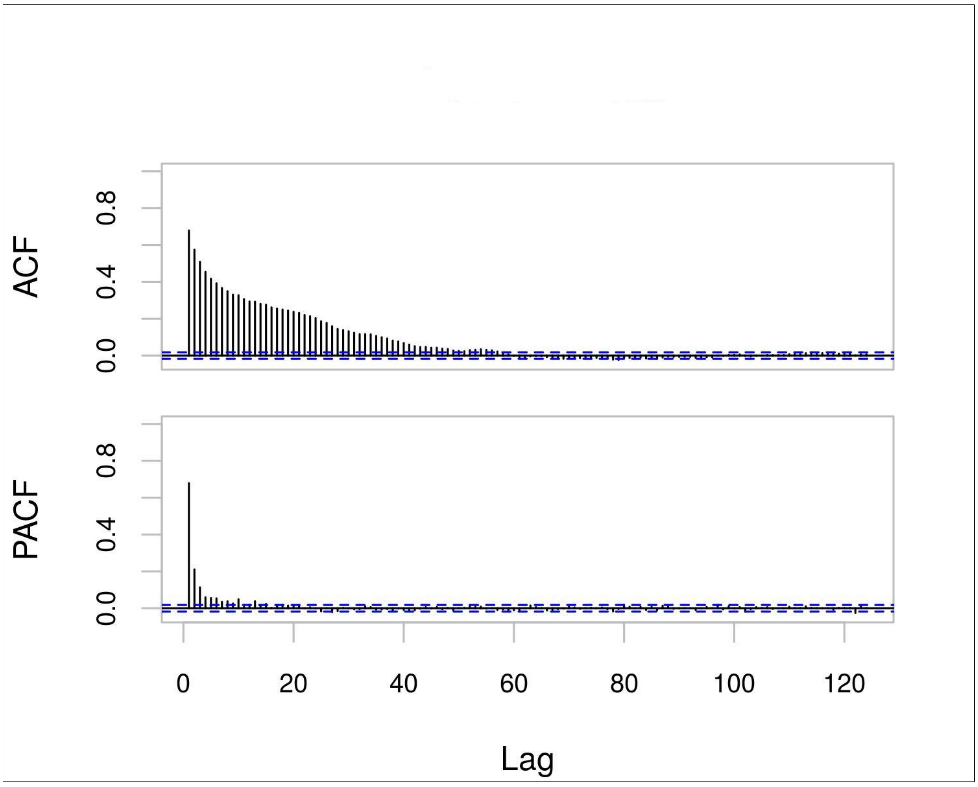
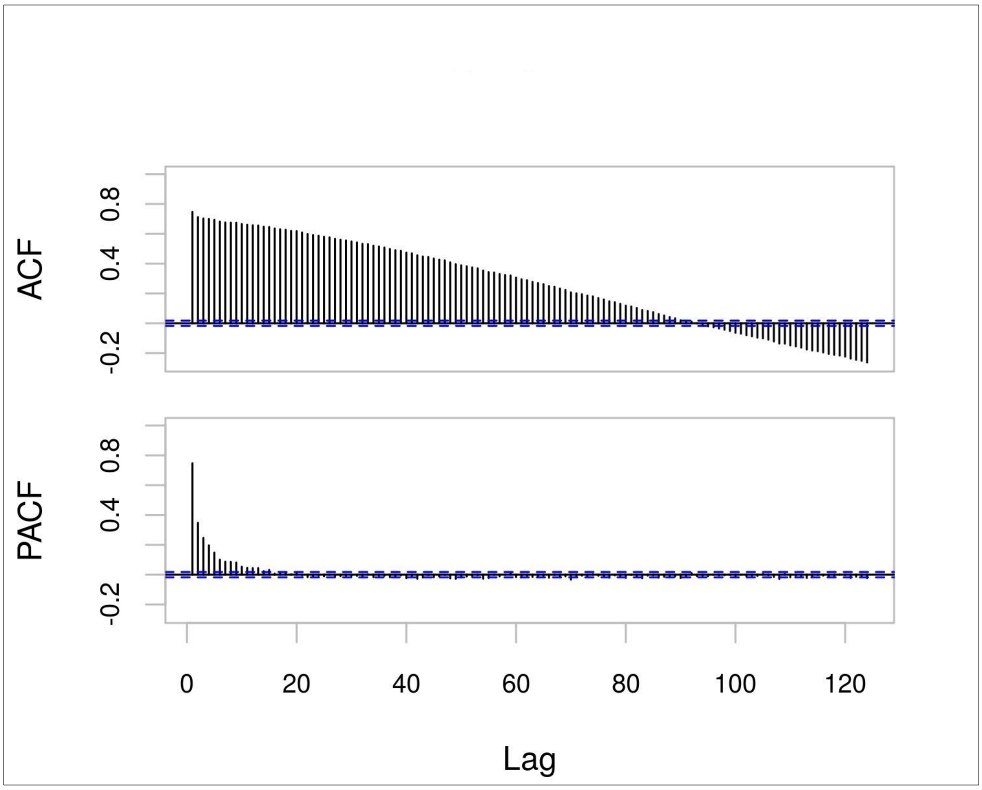


Figure 7 Autocorrelation of minimum and maximum temperature of Asaba station; (up panel) maximum temperature; (down panel) minimum temperature



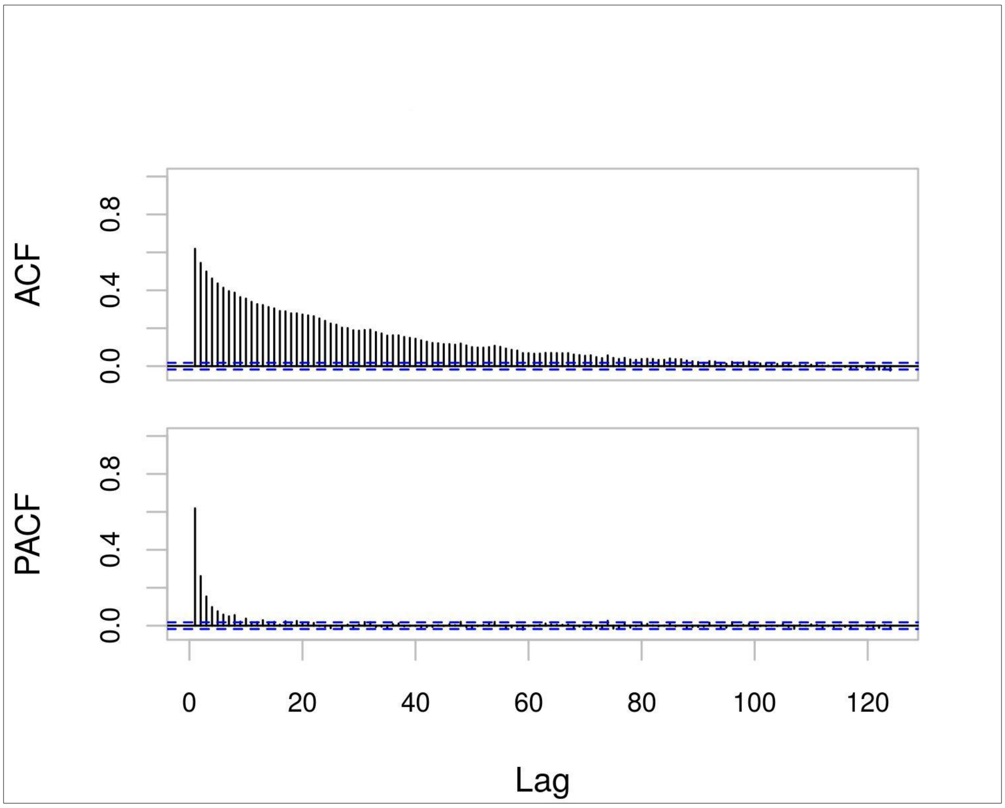
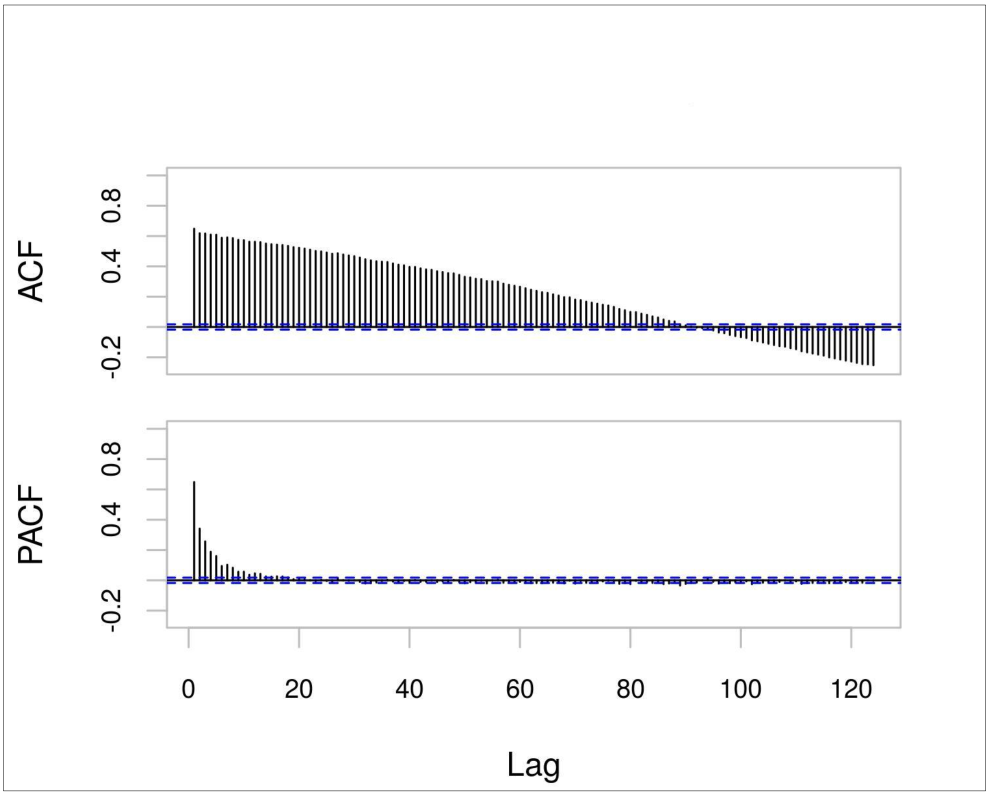


Figure 8 Autocorrelation of minimum and maximum temperature of Benin station; (up panel) maximum temperature, (down panel) minimum temperature



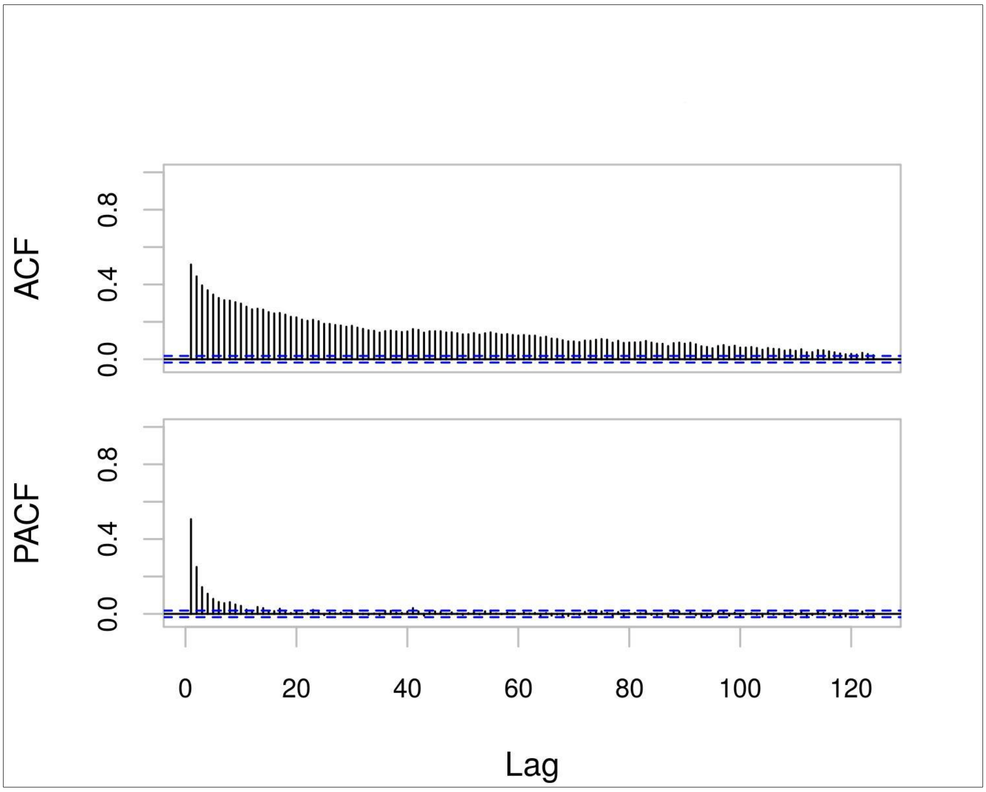


Figure 9 Autocorrelation of minimum and maximum temperature of Calabar station; (up panel) maximum temperature, (down panel) minimum temperature

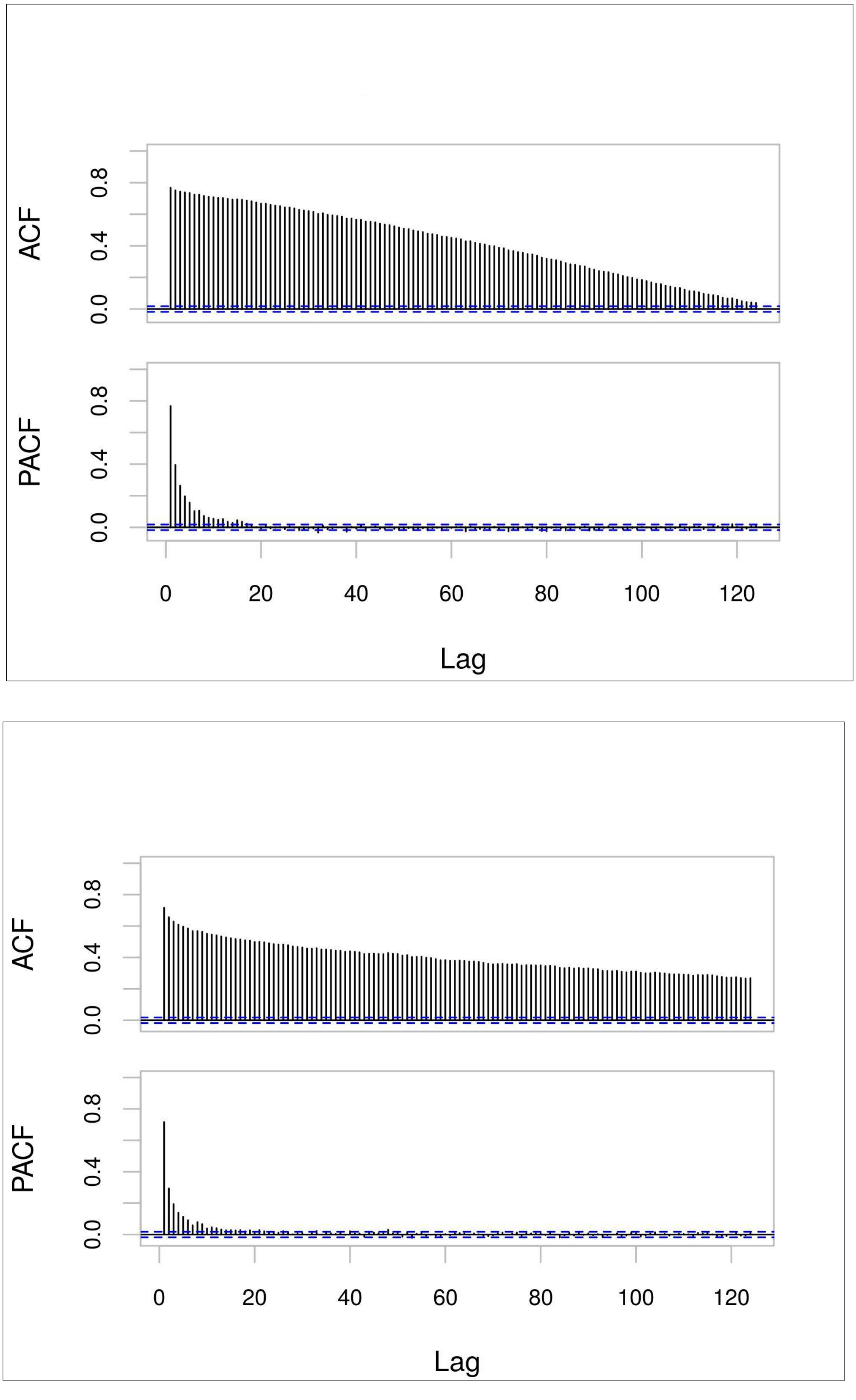


Figure 10 Autocorrelation of minimum and maximum temperature of Eket station; (up panel) maximum temperature, (down panel) minimum temperature

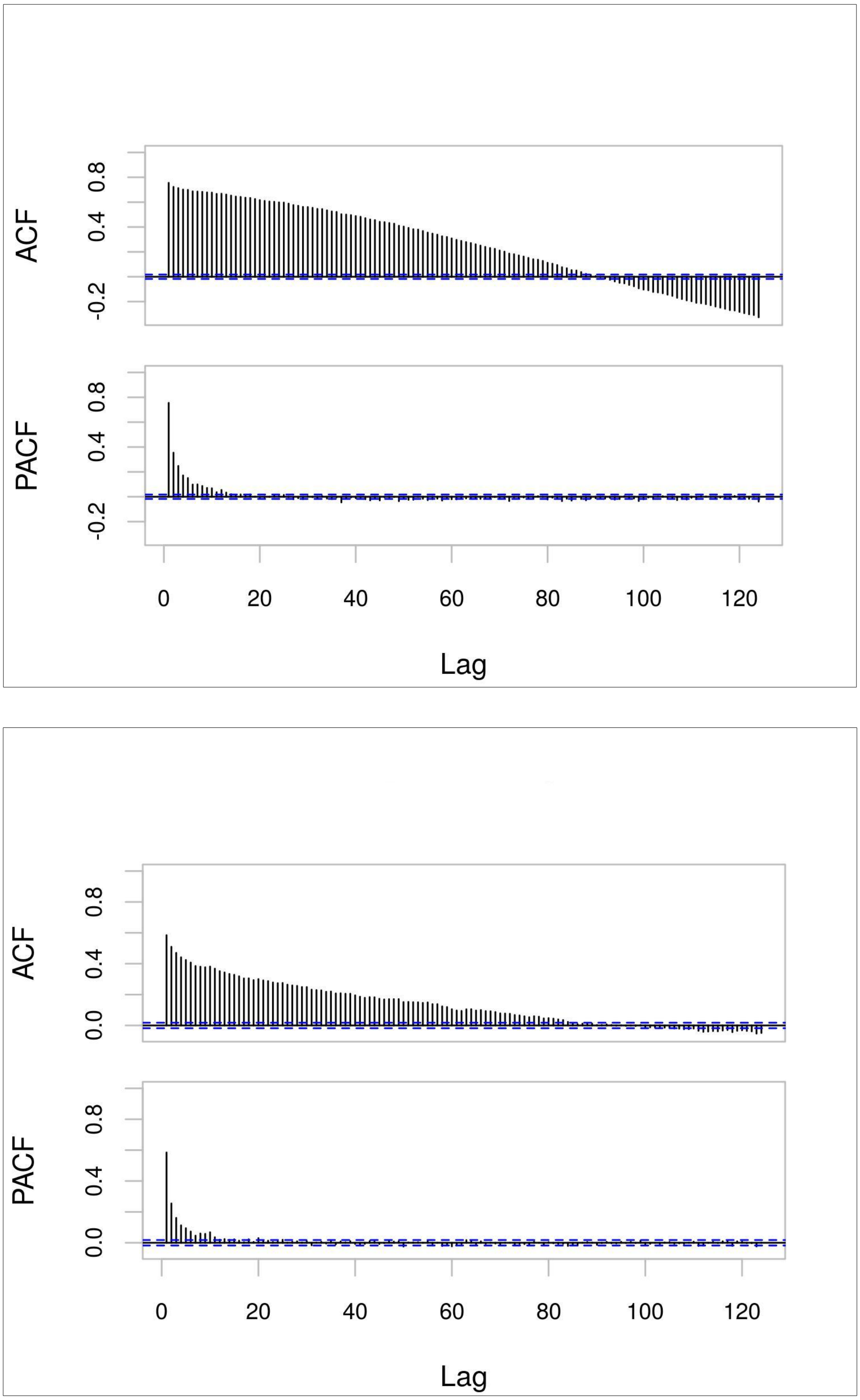
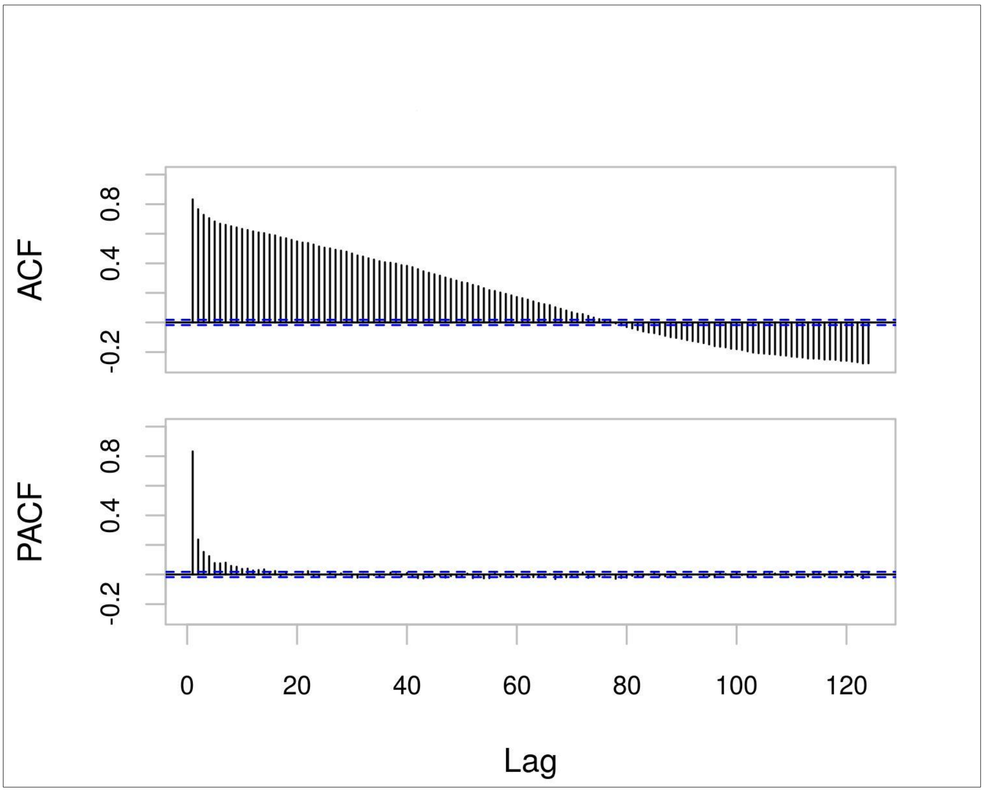


Figure 11 Autocorrelation of minimum and maximum temperature of Ikeja station; (up panel) maximum temperature, (down panel) minimum temperature



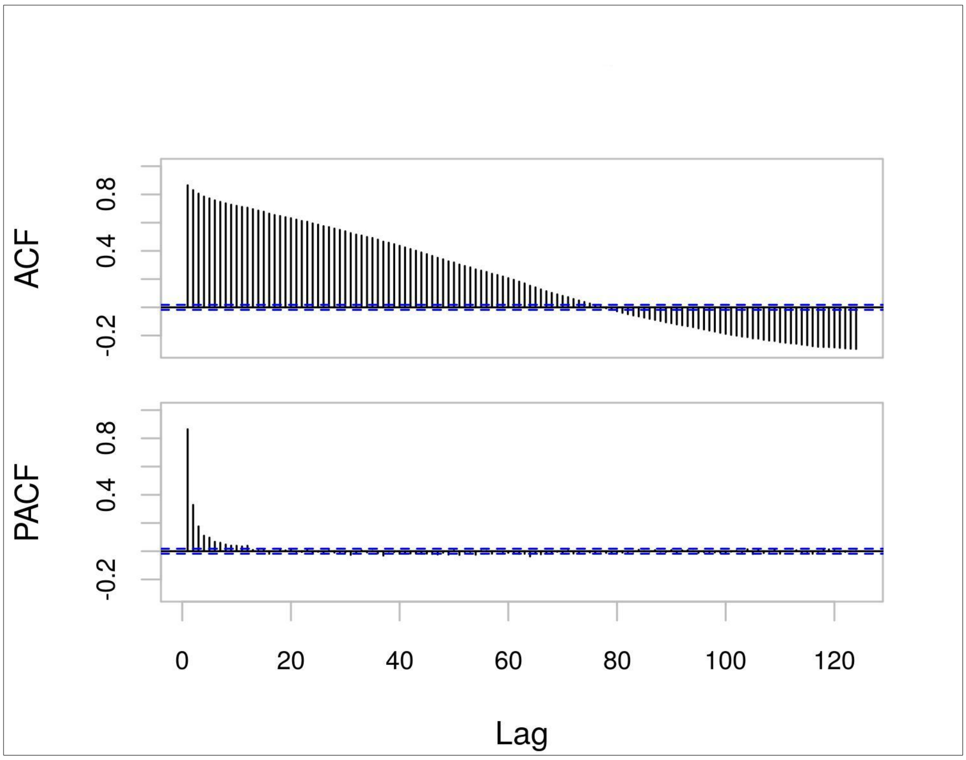
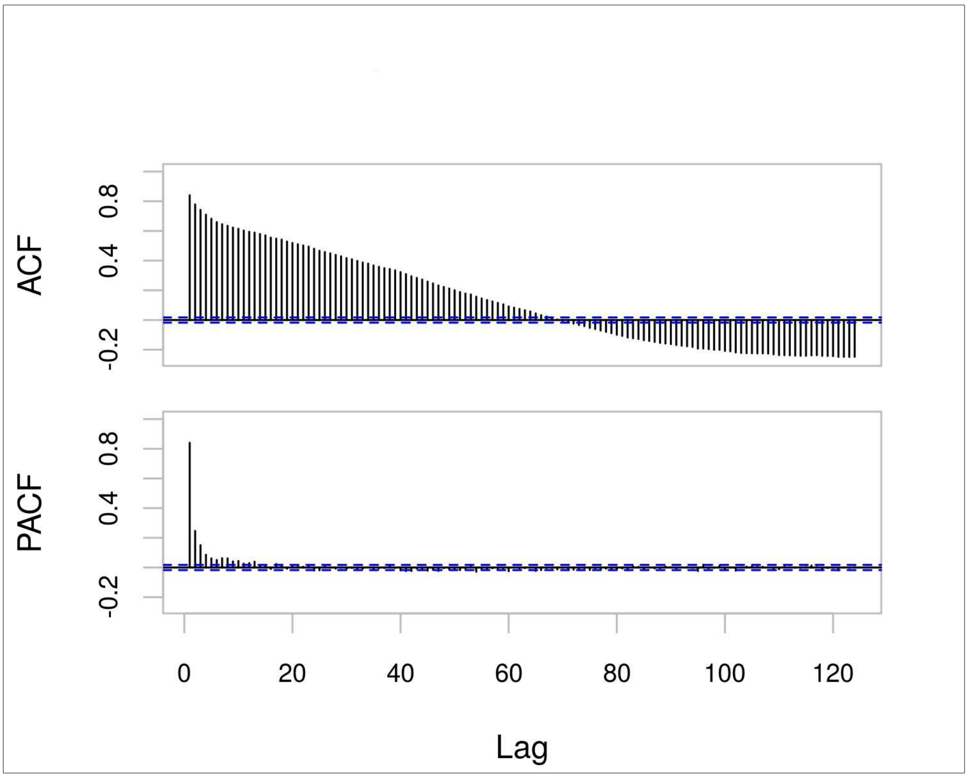


Figure 12 Autocorrelation of minimum and maximum temperature of Jos station; (up panel) maximum temperature, (down panel) minimum temperature



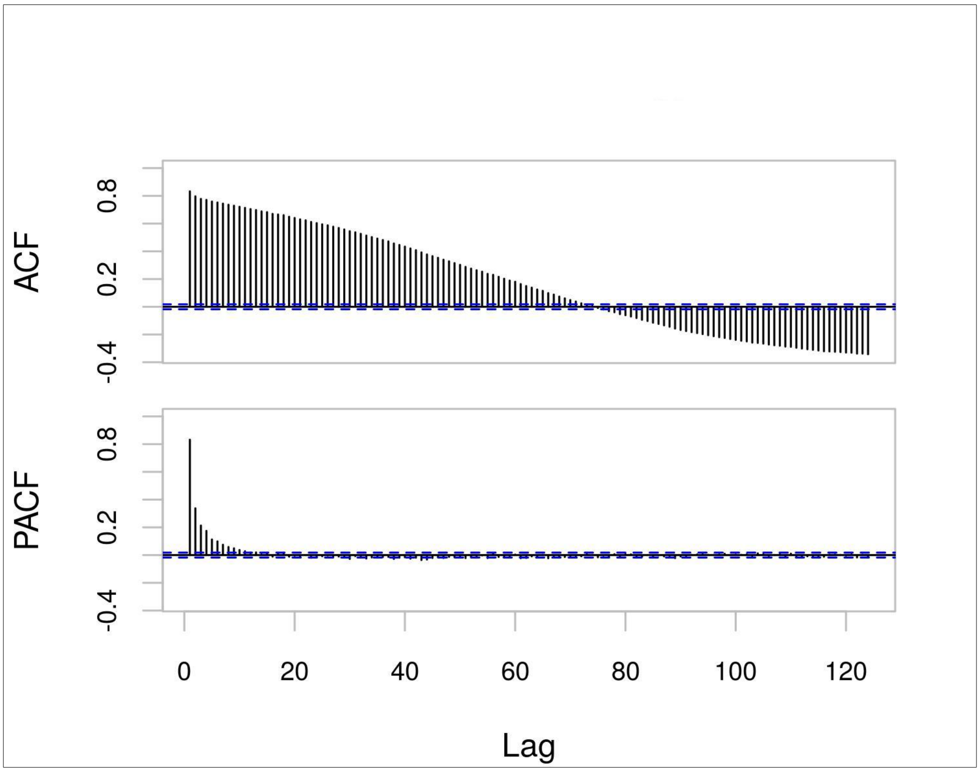


Figure 13 Autocorrelation of minimum and maximum temperature of Kaduna station; (up panel) maximum temperature, (down panel) minimum temperature

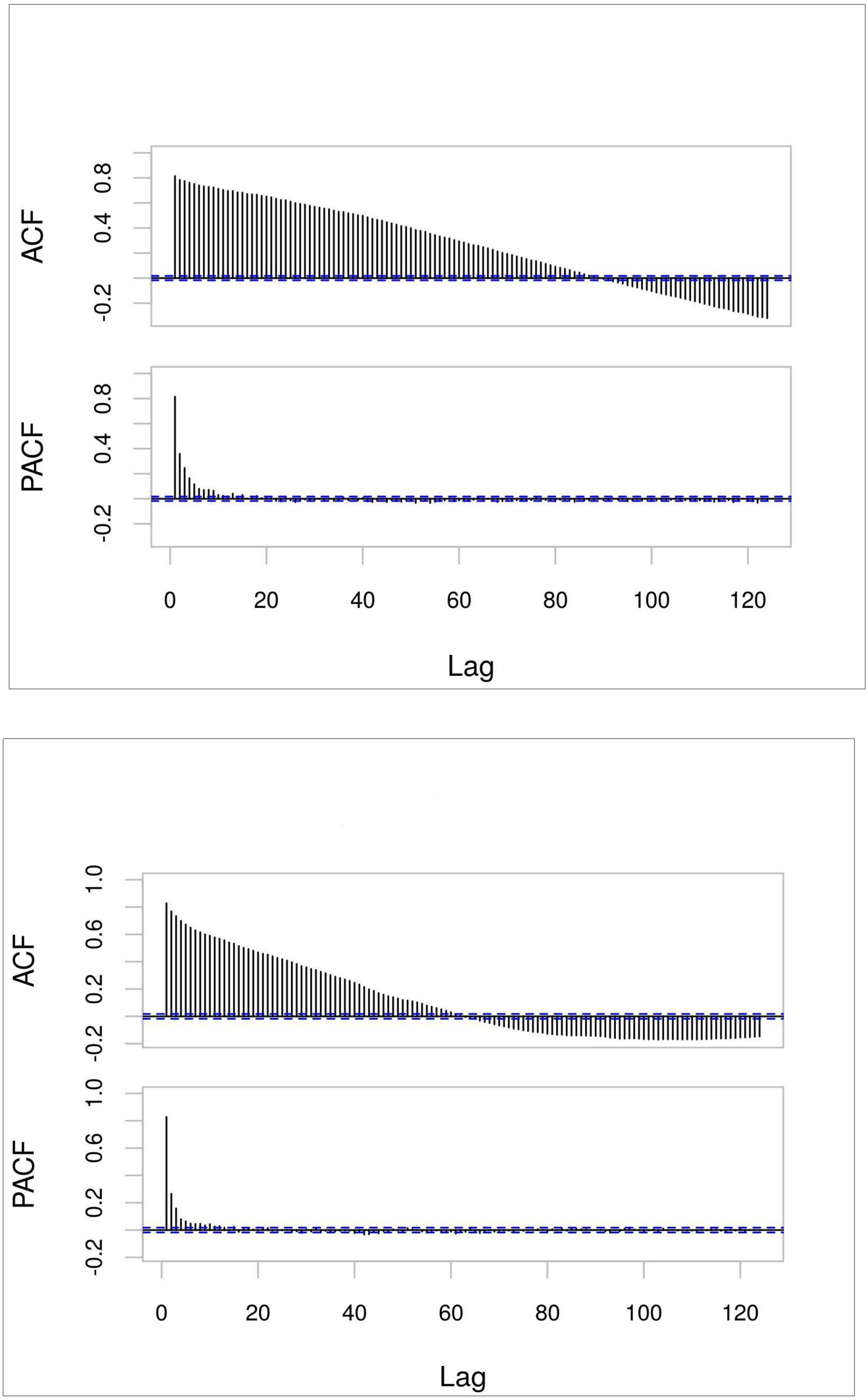


Figure 14 Autocorrelation of minimum and maximum temperature of Lokoja station; (up panel) maximum temperature, (down panel) minimum temperature

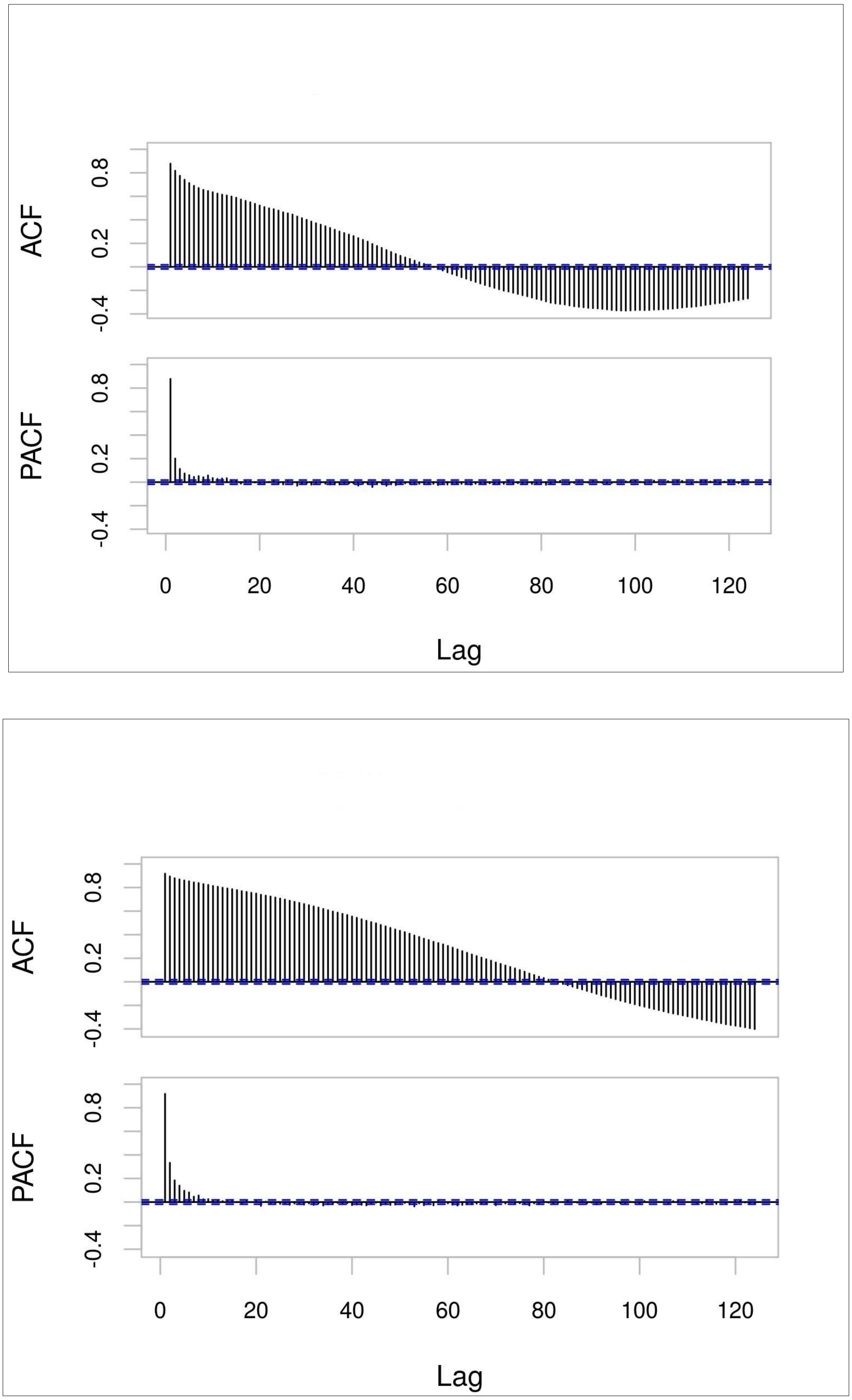
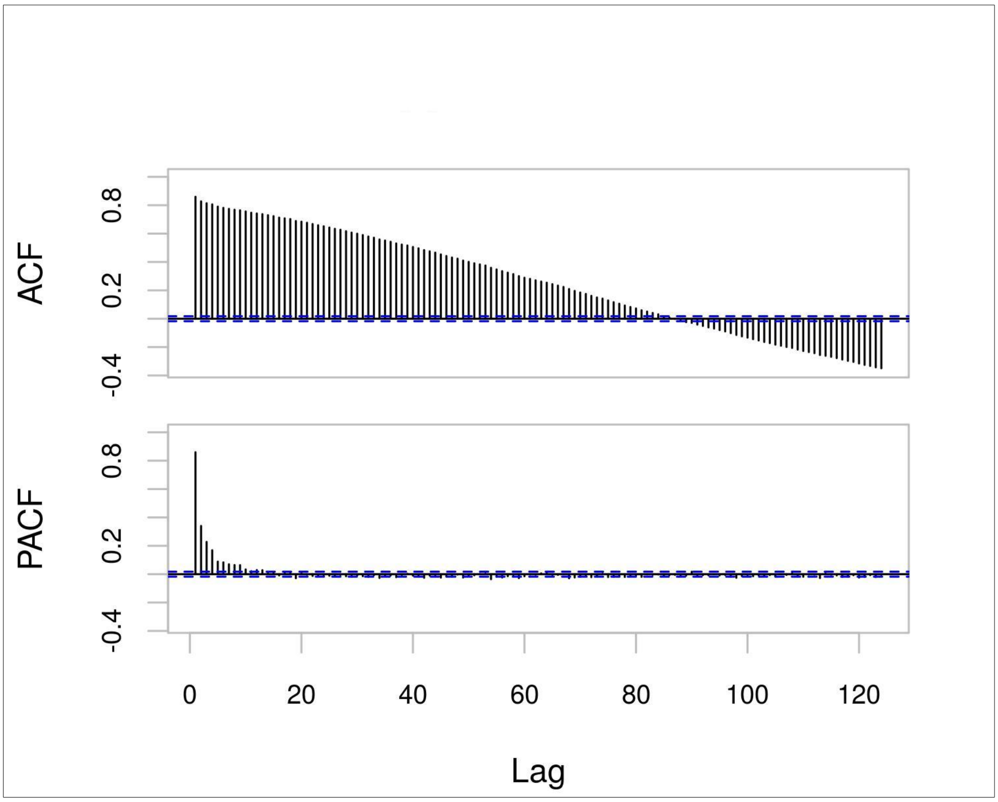


Figure 15 Autocorrelation of minimum and maximum temperature of Maiduguri station; (up panel) maximum temperature, (down panel) minimum temperature



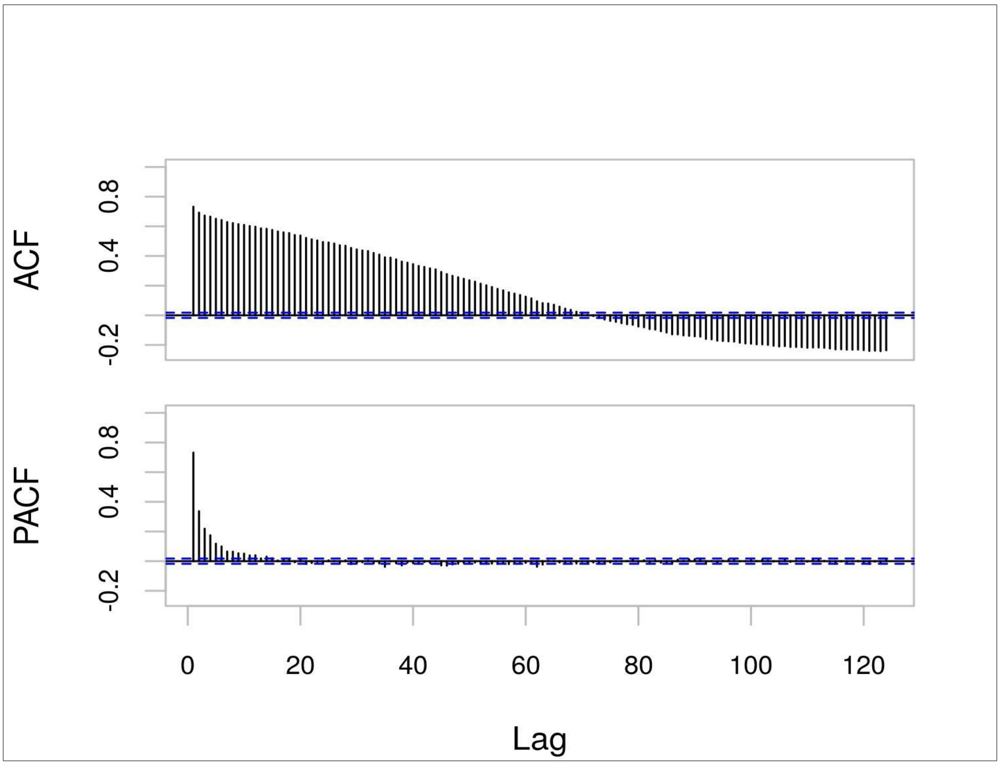
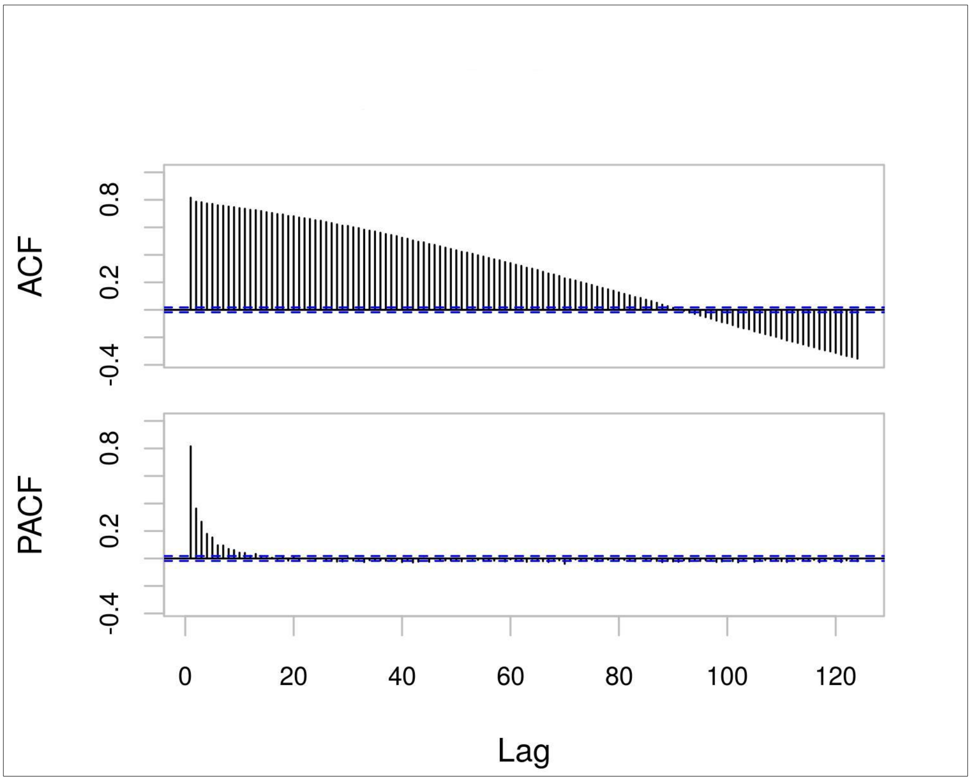


Figure 16 Autocorrelation of minimum and maximum temperature of Minna station; (up panel) maximum temperature; (down panel) minimum temperature



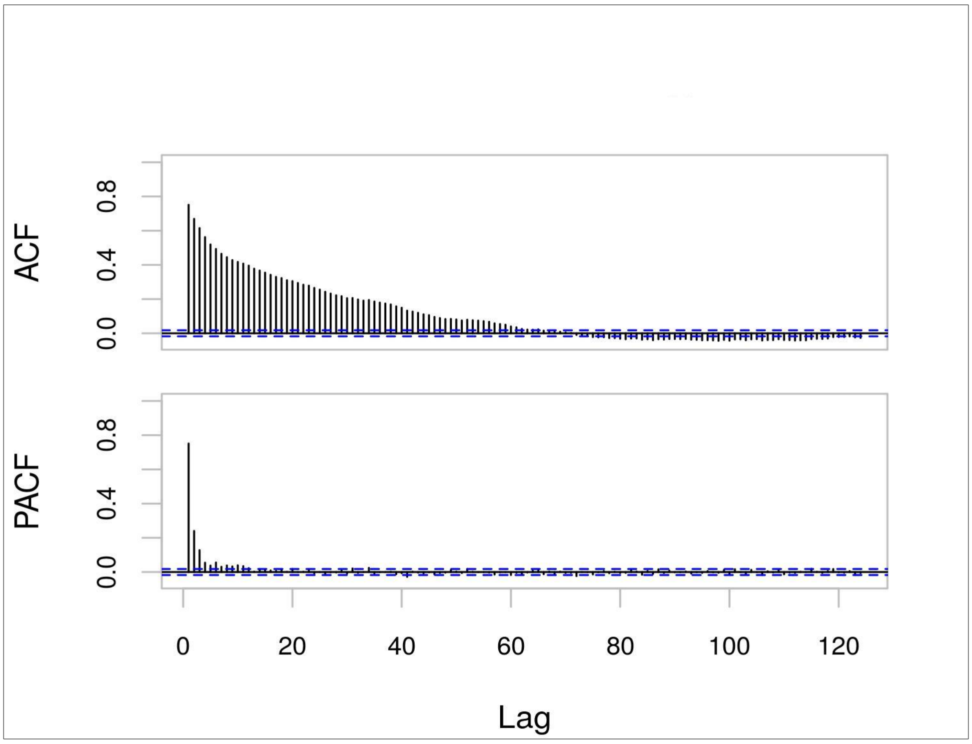
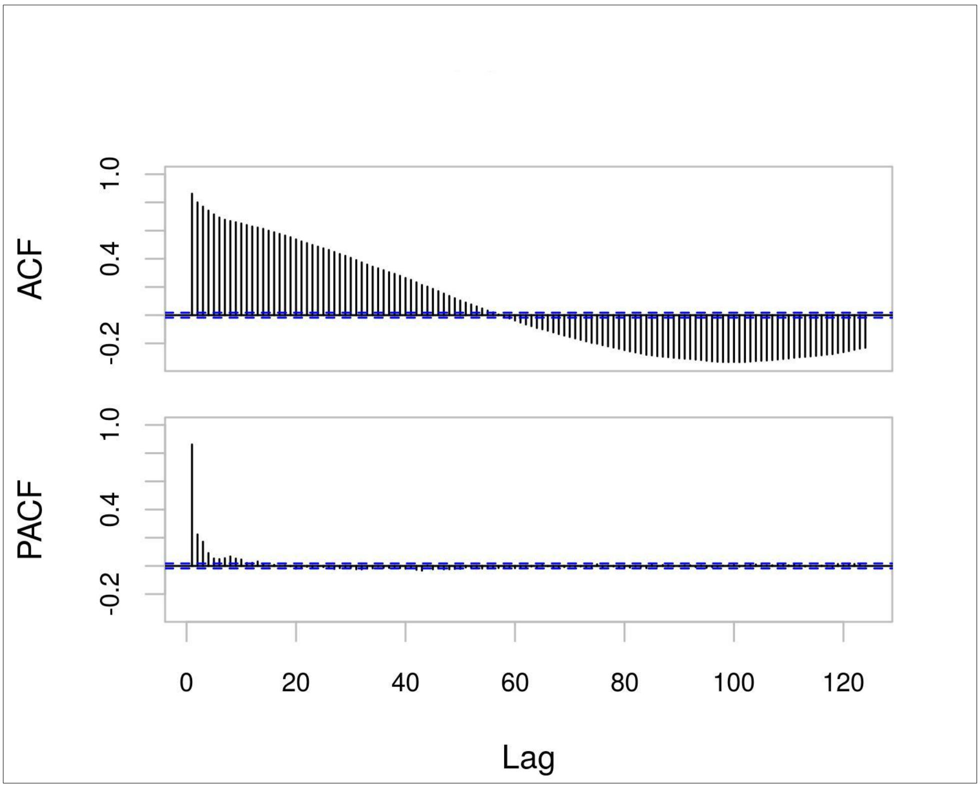


Figure 17 Autocorrelation of minimum and maximum temperature of Oshogbo station; (up panel) maximum temperature, (down panel) minimum temperature



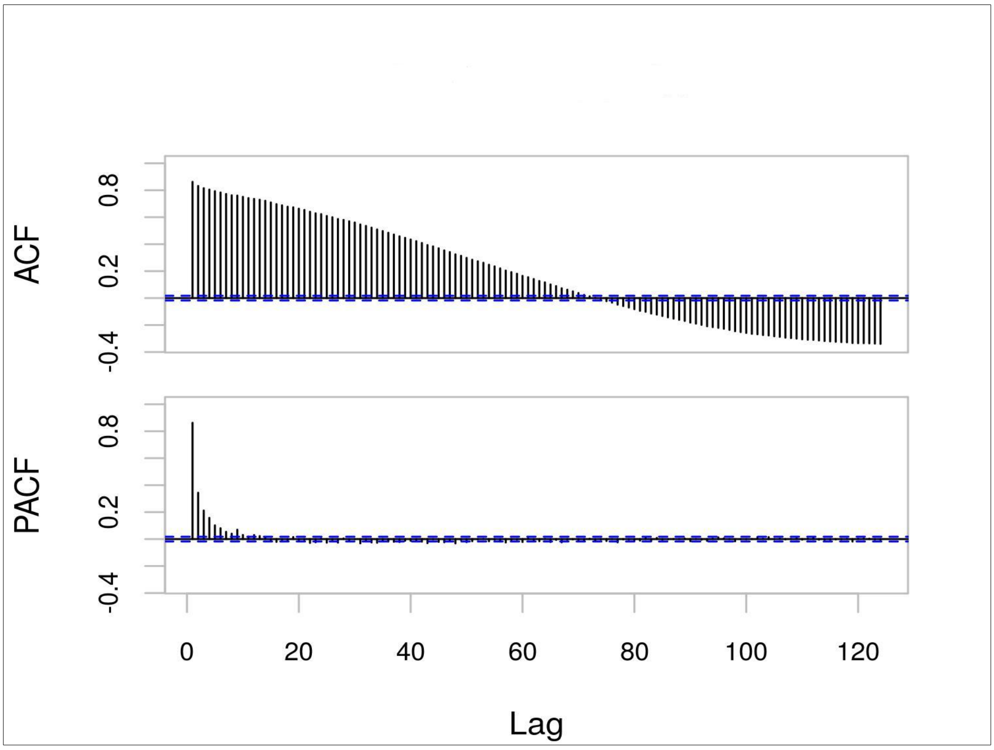
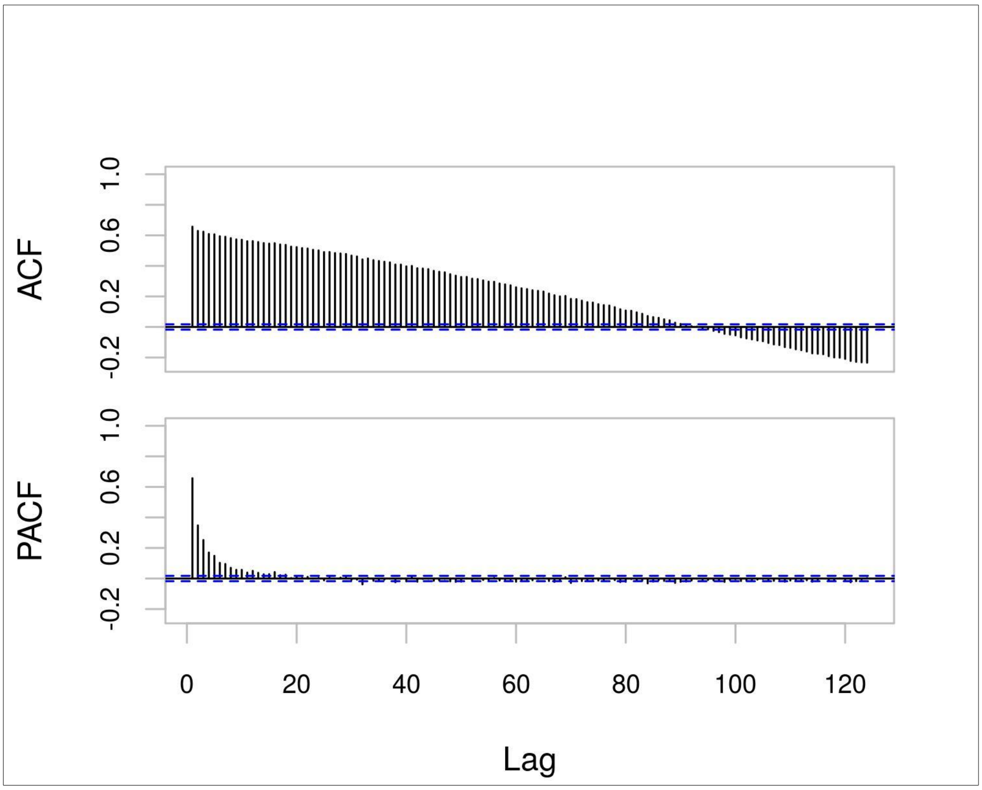


Figure 18 Autocorrelation of minimum and maximum temperature of Sokoto station; (up panel) maximum temperature, (down panel) minimum temperature



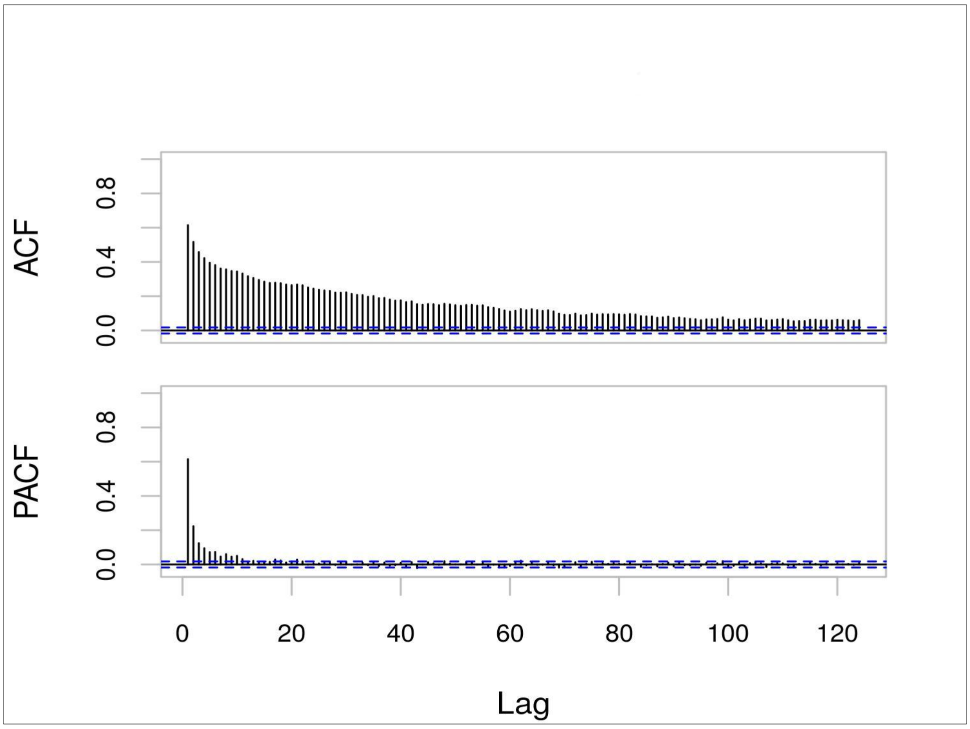


Figure 19 Autocorrelation of minimum and maximum temperature of Uyo station; (up panel) maximum temperature, (down panel) minimum temperature

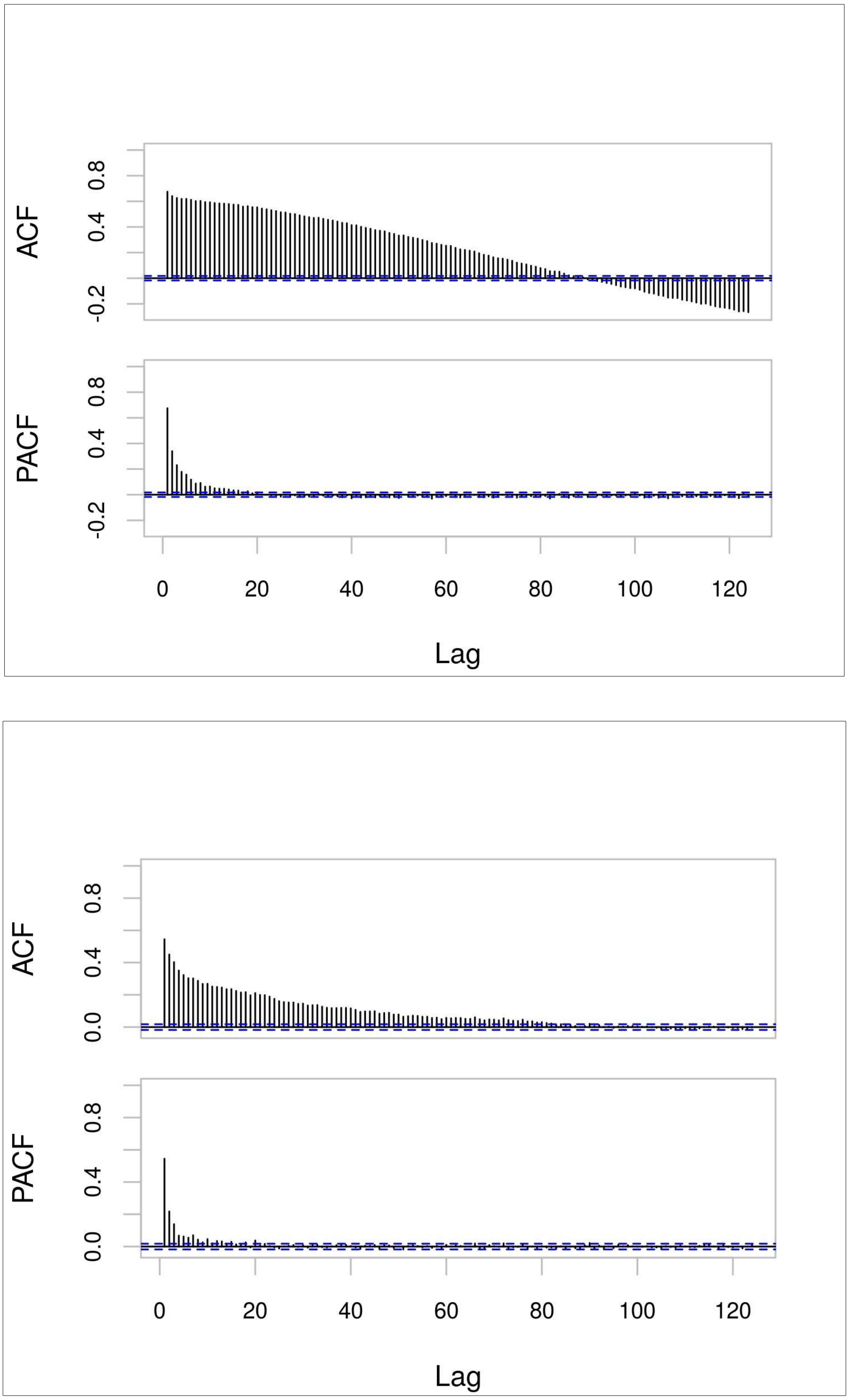
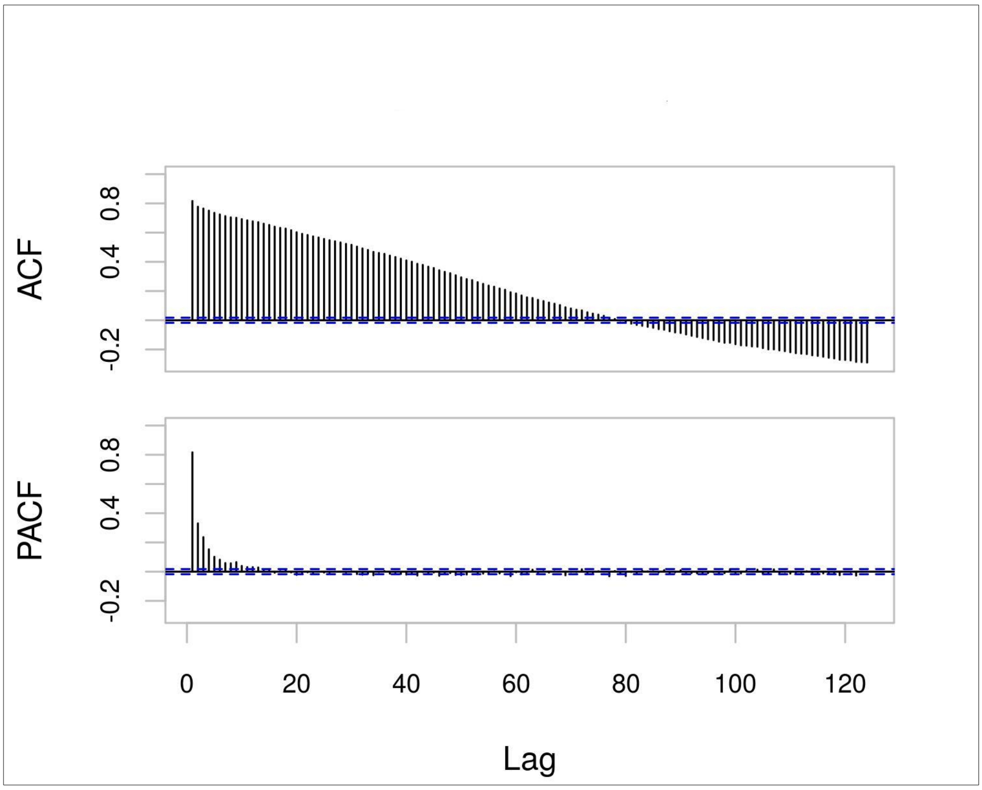


Figure 20 Autocorrelation of minimum and maximum temperature of Warri station; (up panel) maximum temperature, (down panel) minimum temperature



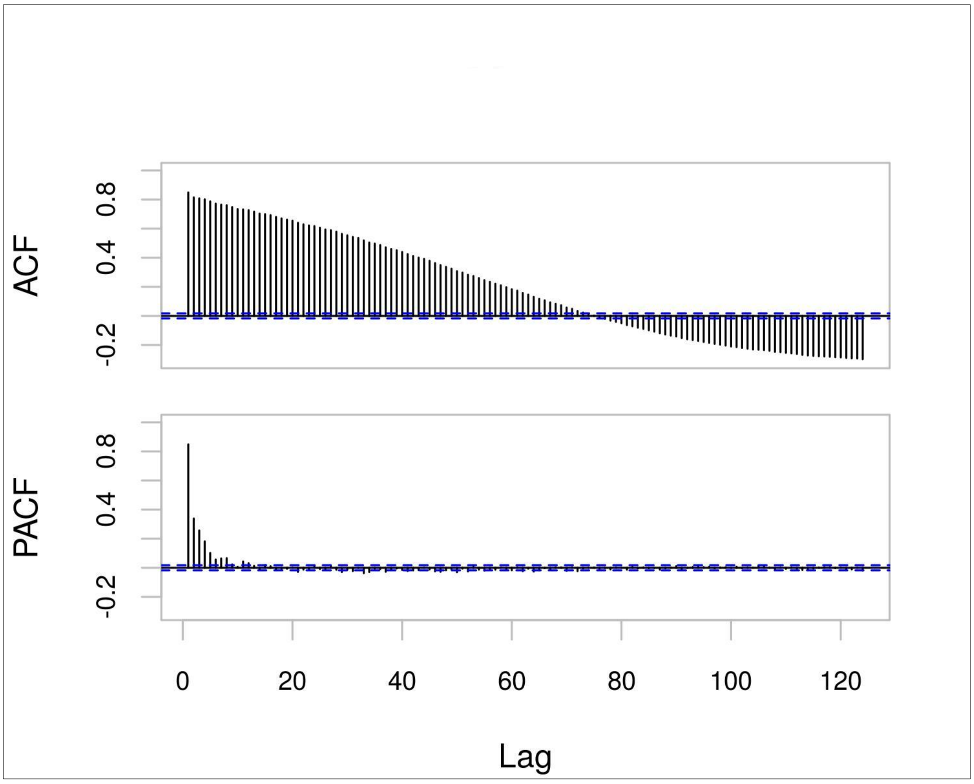
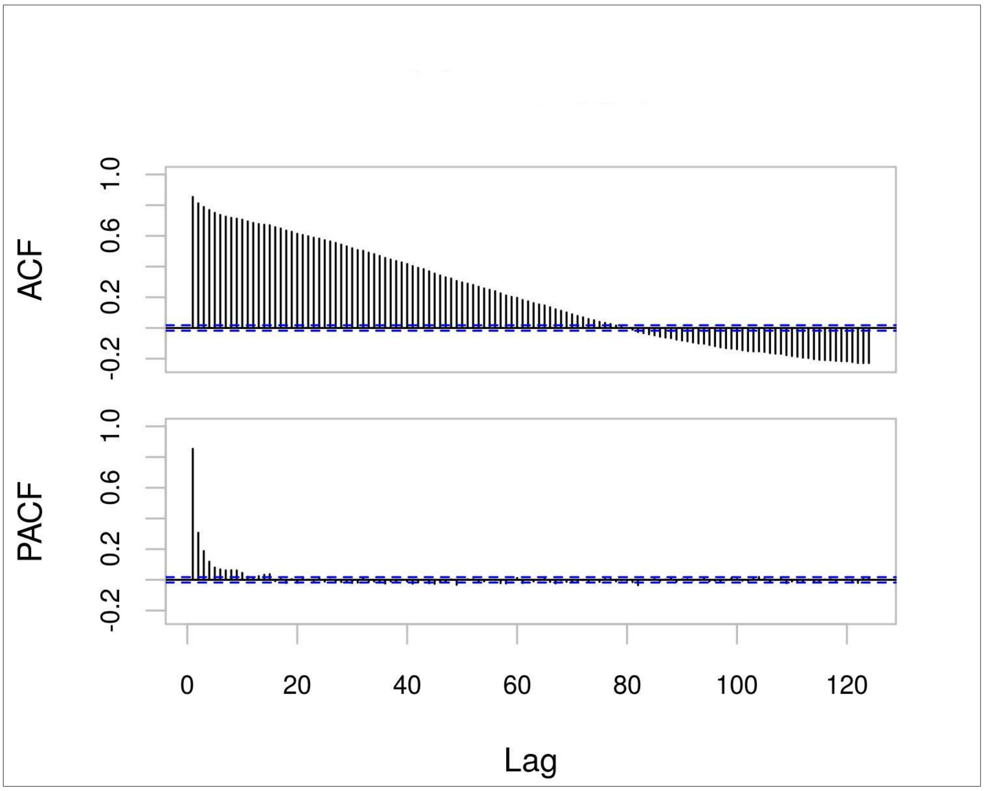


Figure 21 Autocorrelation of minimum and maximum temperature of Yelwa station; (up panel) maximum temperature, (down panel) minimum temperature



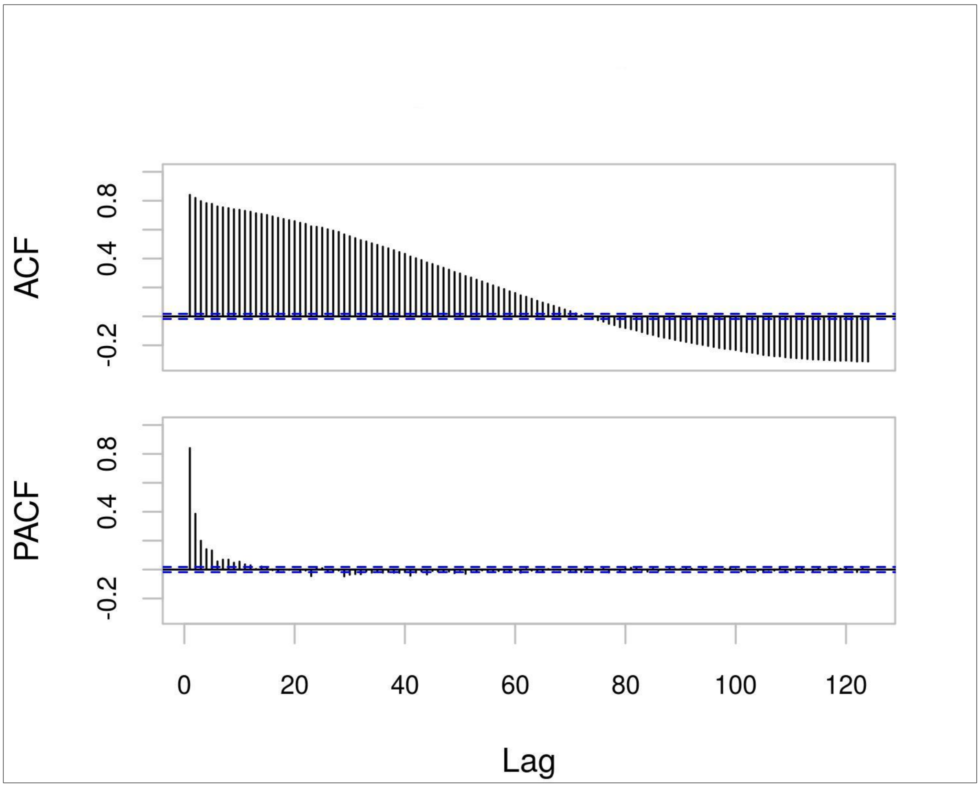
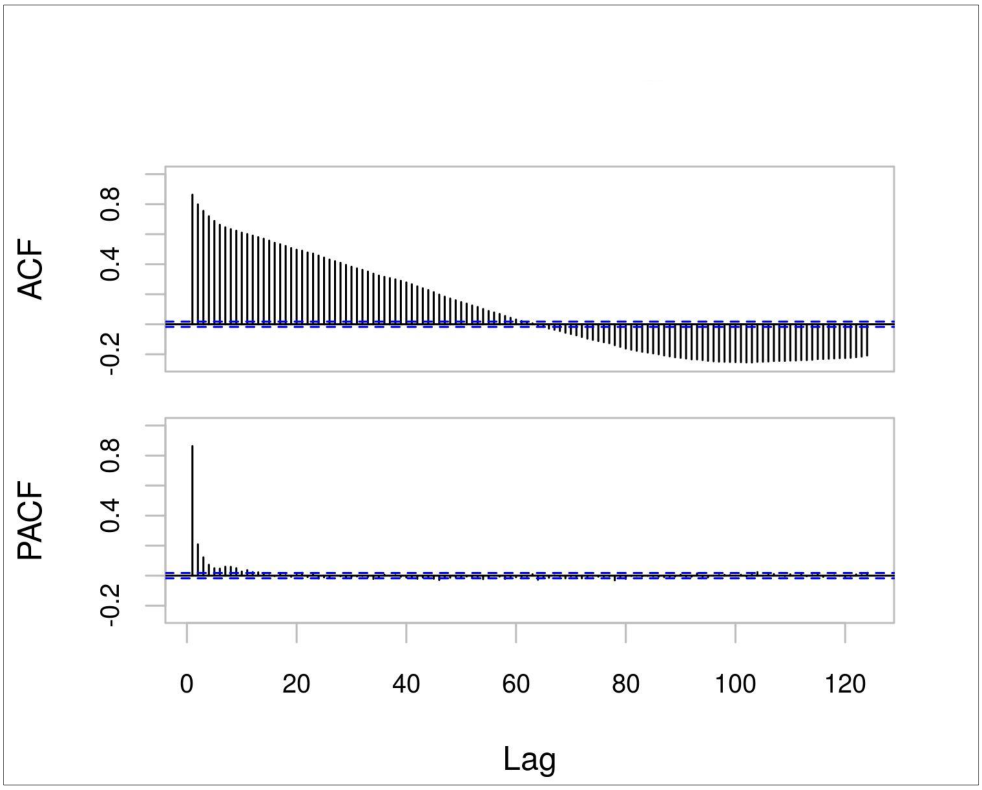


Figure 22 Autocorrelation of minimum and maximum temperature of Yola station; (up panel) maximum temperature, (down panel) minimum temperature



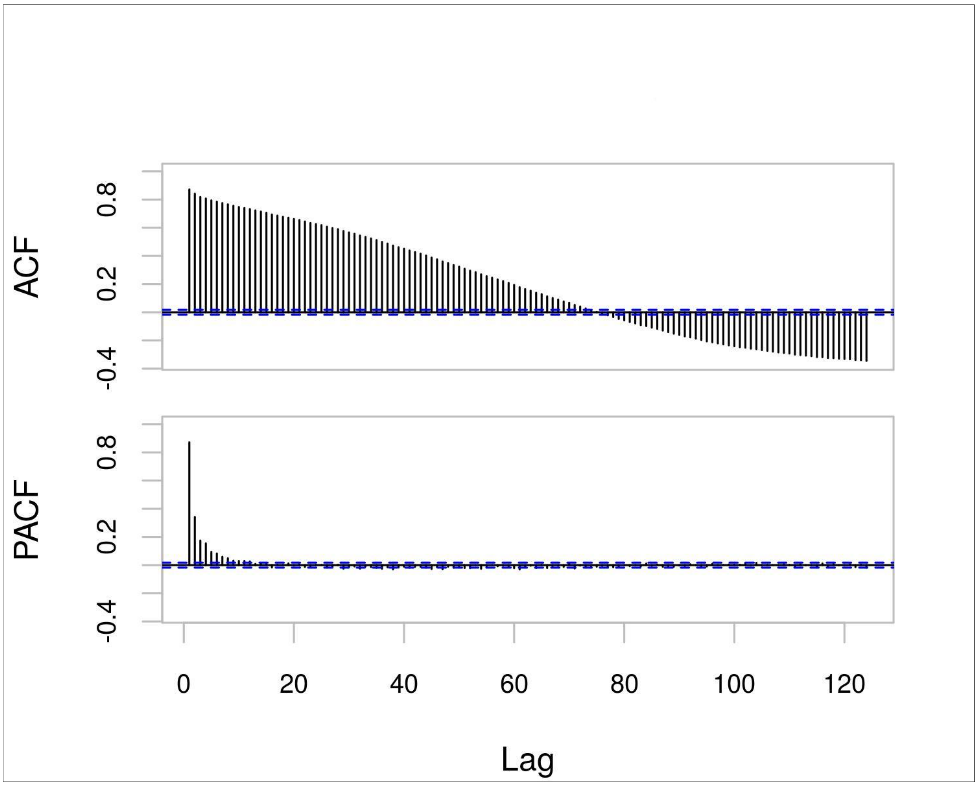


Figure 23 Autocorrelation of minimum and maximum temperature of Zaria station; (up panel) maximum temperature, (down panel) minimum temperature