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ORIGINAL ARTICLE

A change comparison of heat wave aspects in climatic zones of Nigeria

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Abstract

Studies have shown an increase in the frequency and severity of heat waves during the last decades under climate change. This study employs four temperature-based definitions, the percentile based TN90th—the 90th percentile of minimum temperature, and TX90th—the 90th percentile of maximum temperature, the Excess Heat Factor (EHF) and the Heat Wave Magnitude Index daily (HWMId), to investigate the present occurrence of heat waves (1981–2016) in five climatic zones of Nigeria. ERA-INTERIM reanalysis daily minimum and maximum temperature data were retrieved from ECMWF database for the purpose. Five characteristics were studied, the heat wave number, duration, frequency, amplitude and the magnitude. The study of heat wave characteristics in different climatic zones revealed that, from 1981 to 2016, heat waves occurred and covered more zones in the last decades. The first heat wave definitions (TN90, TX90 and EHF) revealed almost the same pattern of heat wave number (HWN) in Nigeria from 1981 to 2016 showing that of 1983, 1987, 1997, 2006 and 2007 where the latter had the highest number of events. The general coverage of the number of events increased from 1999. The Sahel was seriously 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 and compare the intensity of heat waves in the present time and revealed super extreme heat waves (HWMId > 32) in the Sahel and extreme heat waves in the south.

Keywords Heat waves · Climate change · 90th percentile · Excess heat factor · Heat Wave Magnitude Index

Introduction

The century (1906–2005) temperature linear trend of 0.74 °C is obviously lower than the related trend of 1980 to 2012, which is 0.85 °C (IPCC 2014). Indeed climate change has been affecting communities in different ways and climate extremes are part of the most confusing challenges of climate change. The changes in the climate implies changes in the spatial extent, in the frequency, the intensity, the duration, and the time frame of climate events and this can lead to ground-breaking extreme weather and climate events (IPCC 2012). There are different climate extremes that affect communities in different ways: storms, flooding, drought and heat waves. The latter may seem to be the less dangerous among them but the recorded impacts worldwide have been dreadful compared to the other ones during the last decades (Balogun et al. 2016; Ceccherini et al. 2016a, b; Russo et al. 2014, 2015; Nkrumah et al. 2011). From droughts to flooding rains and damaging frosts to heat waves, it is obvious that climate extremes are very important and must be considered in every society (Alexander 2016); especially in tropics (direct hit of sunshine)

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where the west Africa countries are located. These impacts are also felt by human, infrastructure and crops (Ajetomobi 2015, 2016; Lobell et al. 2011; Luo 2011; Le 2011; Lobell and David 2010; Barnabás et al. 2008; Jones and Thornton 2003; Soja and Soja 2003). The European heat wave of 2003 affected mainly France, Spain, Switzerland and England and the deaths were estimated to be more than 40,000. The transportation sector, the energy, agriculture and water resources were affected as well as health. It is now manifest that extreme events such as heat waves destroy properties, injure and kill people, and menace endangered species (CDC 2013). Climate extreme weather and climate extremes have a highly devastating impacts on human societies and ecosystems, and this admits human lives losses, economic and non-economic impairment and ecological responses (Meehl et al. 2000; Parmesan et al. 2000; Jentsch and Beierkuhnlein 2008; IPCC 2012; Reichstein et al. 2013) as cited by Sippel and Otto (2014). The challenges that countries are facing because of climate change are numerous, and Africa is very much affected.

Heat waves occur when high pressure rise upward in the higher atmosphere above the earth, from 3000 to 7600 m, gain strength and stays over an area for days and sometimes weeks in the same place. This physical process is frequently observed in summer (in each of the hemispheres) as the jet stream motion with the sun [National Oceanic and Atmospheric Administration (NOAA), 2015]. Anticyclones with low-level thermal low (transient anticyclones) can alter the jet stream's normal path and block synoptic weather systems and allow heat waves to build in an area. This is a complex system that includes many factors such as tropical convection (Horton et al. 2016). Nigeria is among the most biggest and populated countries in sub-Saharan Africa. The country has just entered into this series of extreme flooding and extreme heat in the northern part of the country with Abuja and even in the south, where the mega-city Lagos is located. An example of such event was recorded in 2016 in Lagos (Muanya et al. 2017) where heat waves affected the whole mega-city. This study uses indices, considering an index as the representation of some particular and extreme aspects of a climate dataset, that have been useful to the study of heat waves patterns in Nigeria.

Daily temperature data with very less or no missing values are required to study climate extreme events especially heat waves. ERA-Interim data were retrieved for the purpose in order to cover the whole of the country with the climatic zones at a fine resolution. The fine resolution allows precision of the results. The study aims to analyse and compare the occurrence of different heat wave aspects in Nigeria. Indices (TX90, TN90 and EHF) were computed with five aspects each. The HWMId was employed especially to compare the recorded heat waves in the world (Russo et al. 2015). The analysis is deployed in the three following steps: (1) collection of climate parameters datasets needed to be run (mainly temperature); (2) calculation of heat wave indices using three definitions and the Heat Wave Magnitude Index daily (HWMId) that represents the fourth index from 1981 to 2016; (3) comparison of the different aspects of the studied indices in the considered climatic zones and with previous heat waves occurring in different places like the European summer and the Russian heat waves.

Materials and methods

Study area

The study area (Nigeria) was divided into five zones namely the Coastal zone, the Tropical Rainforest, the Guinea Savannah, the Sudan Savannah and the Sahel (Akinsanola and Ogunjobi 2014). This division helped to shape the heat wave behaviour in the different determined area over the time and to compare them. The climatic zones are shown in Fig. 1 and classified following the Agro-climatic zones distribution (based mainly on rainfall and temperature) of the country (Ayanlade et al. 2018).

Materials

ERA-Interim dataset (Ceccherini et al. 2016b), 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-h analysis window. ERA-Interim data were downloaded at 0.1°/0.1° (~ 11 km) from the European Centre for Medium-Range Weather Forecasts (ECMWF) public dataset for the period of 37 years, 1980–2016 (January, 01st, 1980 to December 31st, 2016).

The data were retrieved using the Linux batch program "ecmwfapi" integrated into a python code to import the ECMWF Data Servers and have access to the ECMWF public datasets in a programmatic way. This method reduced the time used to download the data and easily subset the area of study. Location specifications have been fixed to "14/2/3/15" as the North/West/South/East successively in geographic latitude and longitude (lat/long) degrees to subset the area to Nigeria. The times 00 and 12 were requested as the forecast start time at steps 3, 6, 9 and 12 that are the forecast times since the last processing (every 3 h from 00 to 12 and from 12 to 00). The data included daily minimum and maximum temperature at 2 m and total daily precipitation. The downloaded data were lon/lat gridded data type. A total of 14,541 grid-size (131 × 111) were acquired for the analysis.

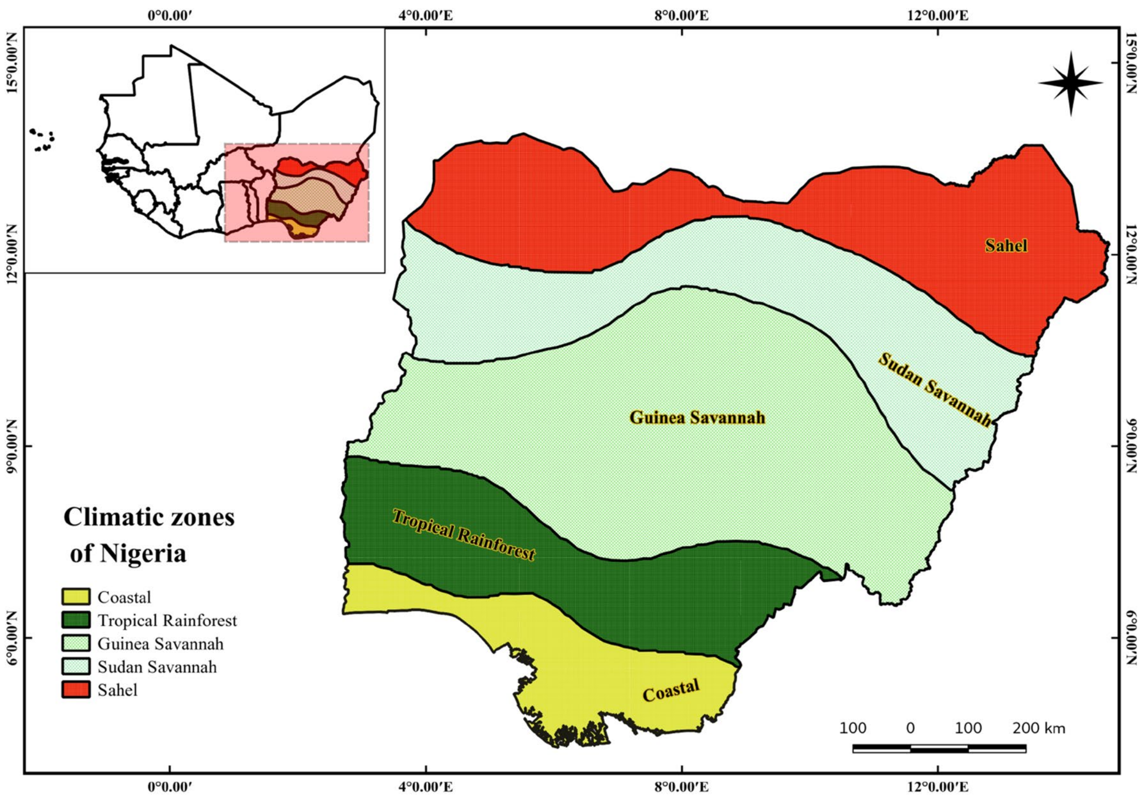


Fig. 1 Climatic zones in Nigeria; adapted from Akinsanola and Ogunjobi (2014)

Methods

A quality control is an important step in the analysis of climate extremes such as heat waves, but for model data there is no need of homogenisation and there have been no homogenisation or quality control on the ERA-Interim retrieved data. No missing values were accounted for the time series. In the analysis of heat waves in Nigeria, four temperature indices were used (summarised in Table 1); the percentile based indices were: the 90th percentile of TX (maximum temperature), TX90th, where the TX > 90th percentile of TX series, and the 90th percentile of TN (minimum temperature), TN90th, where the TN > 90th percentile of TN series. The Excess Heat Factor (EHF) is the third index, used for this study, a combination of two excess heat indices (EHI) representing the acclimatisation to heat (EHI(accl.)) and the climatological significance (EHI(sig.)). Because the two indices are combined together, the EHI(accl.) and EHI(sig.), the EHF is expressed in degrees Celsius squared (°C^2) (see the summary in Table 1). The EHF was developed in Australia by Nairn et al. (2009), and improved by Perkins and Alexander (2013) and Nairn and Fawcett (2013). The definition of Perkins and Alexander, (2013) was used in computing the Excess Heat Factors' heat wave characteristics and occurrence in Nigeria. In ClimPACT2 (an R based software developed by the Expert Team on Sector-specific Climate Indices (ET-SCI), to compute the cores set of climate-related indices. Most of them colligate extreme aspects of the climate, previously developed and partially maintained by the CCl/WCRP/JCOMM Expert Team on Climate Change Detection and Indices [(ETCCDI)—http://www.wcrp-climate.org/etccdi], the EHF was modified (Perkins personal comms 2015) and employed the 90th percentile (instead of using the climatological 95th percentile of TM over the base period) of mean temperature (TM) for each calendar day using a 15-day running window.

A heat wave is defined as 3 or more days where either the EHF is positive, TX > 90th percentile of TX or where TN > 90th percentile of TN. The percentiles are calculated from base period specified on 32 years. Five aspects of heat wave were analysed using the TX90th and the TN90th temperature based indices:

- The yearly number of heat waves (HWN), the heat wave events (≥ 3 heat wave days), that begin in the period of interest in addition to those that start prior to it but continue into the period of interest,

Table 1 List of heat wave indices

N°	Metric	Description	Reference
1	TX90p Amount of hot days	Percentage of days when TX > 90th percentile. Fraction of days with hot day time temperatures Used 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 > 90th percentile Fraction of days with warm nighttime temperatures Used time scale = annual	ETCCDI (http://etccdi.pacificclimate.org/list_27_indices.shtml) Alexander et al. (2006)
3	EHF Excess Heat Factor	Considers daily TX and TN: T=(TX + TN)/2 includes an acclimatisation 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.)] By multiplying the EHI(accl.) and EHI(sig.) indices, the EHF unit is expressed in degrees Celsius squared (°C^2) (Perkins and Alexander 2013)	Excess Heat Factor (EHF) developed by the Bureau of Meteorology EHF = excess heat * heat stress Nairn and Fawcett (2013) Perkins and Alexander (2013)
4	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 90th percentile of daily maxima, centred on a 31-day window Therefore, for a given day, the threshold is the 90th percentile of the set of data	Russo et al. (2015)

- The duration of the longest yearly event (HWD), length in days of the longest heat wave defined by HWN,
- The yearly sum of participating heat wave days, heat wave frequency (HWF), number of days contributing to heat wave defined by HWN (called heat wave days),
- The warmest day of the hottest annual event (HWA), the off-peak daily value in the hottest heat wave and
- The average magnitude of all annual heat waves (HWM), the mean of the mean heat wave days of each heat wave defined by HWN. The HWMId was also used to determine and compare the HWM.

The ET-SCI indices are application-relevant and sector-specific taking into account health, agriculture and food security and also water resources and hydrology. This study focuses on agriculture-related indices.

The HWMI has been developed and introduced by Russo et al. (2014) and improved to the HWMId by Russo et al. 2015. This index was added to the indices in the study to allow easy and logical comparison of the Nigerian heat wave magnitudes not only to the different climatic zones in the country, but also to the occurred heat waves in the world in intensity and frequency. Details of the computation of HWMId could be found in Russo et al. (2015). The study considered 32 years as reference year (1980–2011) in an R script using the “extRemes” package. The applied scale is the one introduced by Russo et al. (2015) (see Table 2) and used in a study of heat wave in South America (Ceccherini et al. 2016a). The HWMId was computed on TX and TN in this study. A heat wave is again defined here 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 heat waves that occurred in various regions.

Table 2 Heat Wave Magnitude Index daily (HWMId) classification; adapted from Ceccherini et al. (2016a)

Classification	Heat Wave Magnitude Index daily (HWMId)
Normal	1 ≤ HWMId < 2
Moderate	2 ≤ HWMId < 3
Severe	3 ≤ HWMId < 4
Extreme	4 ≤ HWMId < 8
Very extreme	8 ≤ HWMId < 16
Super extreme	16 ≤ HWMId < 32
Ultra extreme	HWMId ≥ 32

A minimum of 30 years was needed as reference to compute the heat waves indices, in the four (4) definitions.

In this study, 32 years were used as reference from 1980 to 2011. Only the extended period of May to September was considered. Leap years have been removed for all the definitions.

A Hovmöller plot was used to determine the trend or time evolution in the heat wave characteristics (Martius et al. 2006) in Nigeria. Hovmöller diagram (Hovmöller 1949) is used in this study to depict or highlight the changes of the heat wave characteristics over the time on a latitudinal line. The Hovmöller plot builds an average of all the heat wave values in a single column of latitude (horizontal X axis) and puts them on one axis. The Y axis carries the time. The latitudes will easily allow to determine the changes in the different latitudes corresponding to the climatic zones. This is to show how heat waves move north or south over the year.

The results were subjected to Mann–Kendall and Sen's slope test in R in order to determine the existence of trends in the time series. 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 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 time series analysis (Deo et al. 2005; Önöz and Bayazit 2003). The Mann–Kendall test is used to evaluate the trend and the slope in the time series of the computed heat waves. The associated Sen slope developed by Sen (1968) estimates the magnitude or the slope of the trend. Spatially centralised data of the results were used.

Results and discussion

Heat wave number (HWN)

The results show that heat wave events occurred in Nigeria since 1981 and the number varies from no events (0) in some area to 19 events a year for TX90 as shown in Fig. 2a. In 1983 and 1987 the high HWN were 8 and 10, respectively, and the highest numbers were located in the north covering Zamfara, Borno, Yobe, Jigawa, Sokoto and Kebbi States. The southern part of Nigeria recorded also heat waves of 3–5 events/year especially from 1996 to 2000 that continues to the eastern part of the Coastal and Tropical rainforest. The primary area were in the south east with Bayelsa, Imo, Anambra, Rivers and Abia States. In the 2000s the heat waves covered almost all Nigeria with an increased number of events. The year 2007 experienced the highest number of events with 19 events in the eastern part of the country. The number of events increased from 2009 to 2016 with an average of 4–8 events/year. In Fig. 2b, the Hovmöller plot highlighted in 1987 and 1988 (in the Sudan Savannah and the Sahel) high numbers of events that increased in the 2000s especially from 2006 to 2010 mainly in the Guinea and Sudan Savannah.

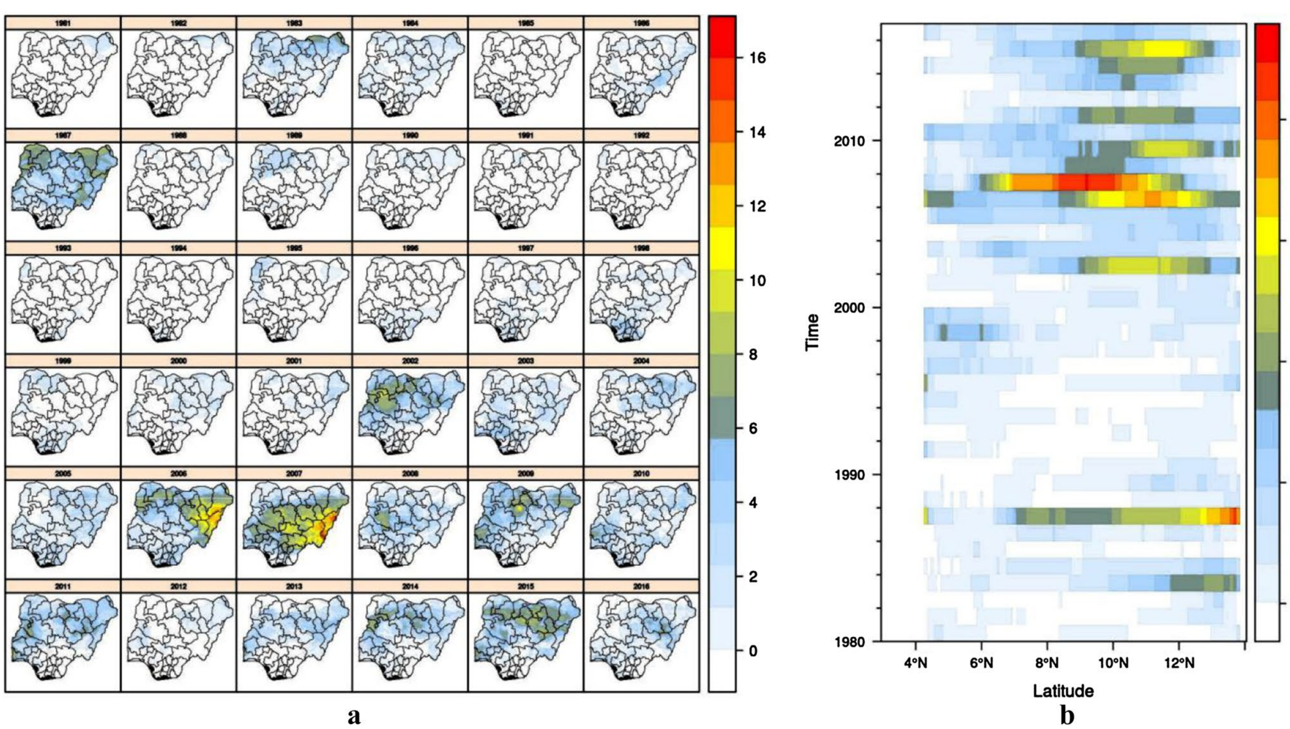


Fig. 2 Heat Wave Number (HWN) of Nigeria using TX90: **a** yearly distribution; **b** Hovmöller graphic

The HWN for TN90 follows the same pattern as 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 spreading over all the Coastal and Tropical Rainforest zones and entering into the Guinea Savannah. Heat waves of minimum 2 number of events occurred everywhere in Nigeria in 1983, and from 2005 to 2016, while the year 1992 showed a particularly low HWN in the country (HWN = 1). From 2006, the high numbers were found more in the Sudan Savannah and Sahelian zone. In general, the Sudan and the Sahel had the highest HWN. The Hovmöller plot (Fig. 3a) showed and increase in the events/year of HWN in the last decade after 1987–1988 events.

The HWN using the EHF definition is similar to the previous definitions of HWN (TX90 and TN90) in terms of spatial occupation. In 1981 the HWN were located in the Sahel, in Borno, Yobe, and Jigawa and started coming down to the Sudan Savannah. The years 1983 and 1987 were particular with almost all the country affected (especially the Sahel and the Savannah zones) with 12 events in the Sahel. The Southern part (Coastal and Tropical Rainforest zones) was particularly involved 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. The EHF also showed an increase in the last decade from 2006 (Fig. 3b).

Heat wave duration (HWD)

Figures 4 and 5 show the HWD in Nigeria. For TX90 heat waves, the duration varied from 1 to 25 days for the longest heat wave of the period 1981–2016. In 1983, the Sahel recorded 18 days and the Sudan Savannah 5–10 days. The Tropical Rainforest and the Coastal zones registered less than 3 days. Sokoto State had 21 days in 1984. The year 1987 also read 14 days in Yobe and Borno and 11 in Kaduna, Zamfara and some parts of Plateau State. Cross river in 1996 had a 8-day-long heat wave. In 2008 the central part (Sudan Savannah), with Niger State, around Minna was affected by a 14-day heat wave while the eastern part of the State had a 12-day heat wave in 2014. A general increase in the HWD using TX90 is observed from 2000 affecting especially the Guinea and Sudan Savannah and the Sahel. A highlight was seen in the Sahel in 1984 and in 2007 in the Guinea and Sudan Savannah.

For TN90 heat waves, 1983 and 1987 recorded different durations across the country and the different climatic zones. The year 1983 read 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 1990s heat waves were very short (2–8 days), but in the 2000s more areas were affected by heat waves of 8–10 days. For example, in 2009 Borno State was impacted by 16 days and in 2015 the south has been covered by 10–15 day-long heat wave. The TN90 showed similar pattern to the TX90, but with a peak in 1987–1988 instead of 2004. From 2005 the HWD covered all the zones with 8–12 days as longest heat wave events (see Fig. 4 for the spatio-temporal plot).

The same results were obtained with HWD for EFH, where 1983 was having 20 days in the Sahel and 5–10 days in the Sudanian zone. Borno is the most affected but

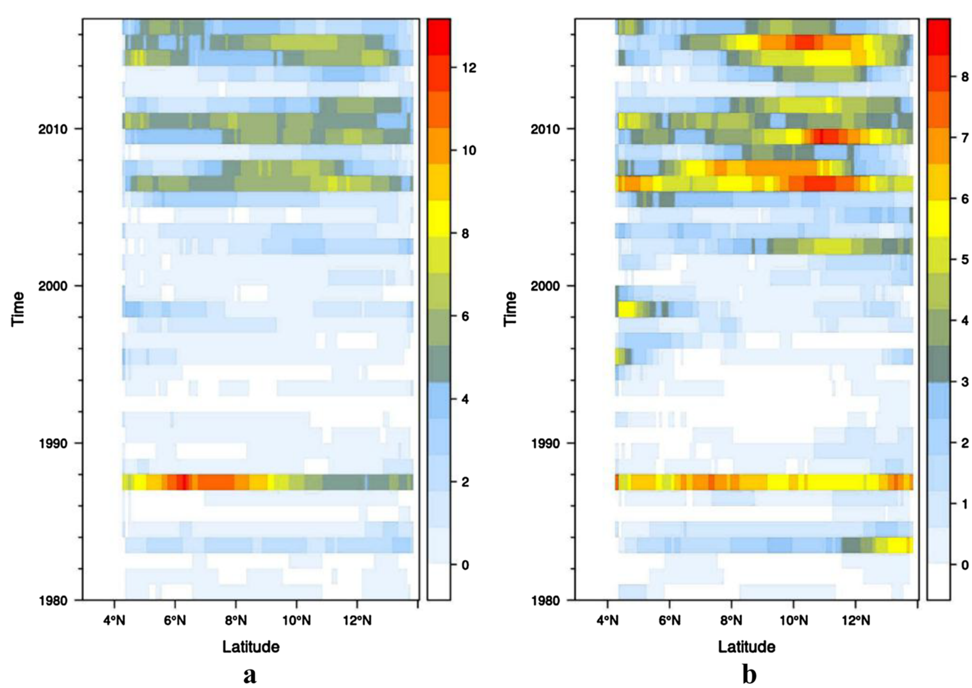
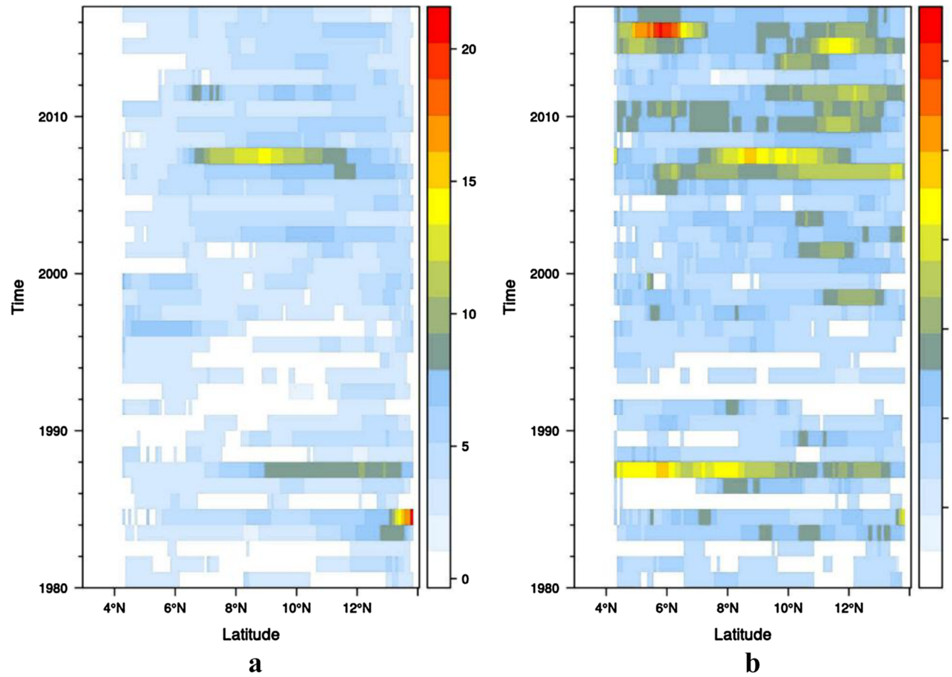


Fig. 3 Heat Wave Number (HWN) of Nigeria, Hovmöller: **a** TN90 **b** EHF

Fig. 4 Heat Wave Duration (HWD) of Nigeria, Hovmöller: **a** TX90 **b** TN90



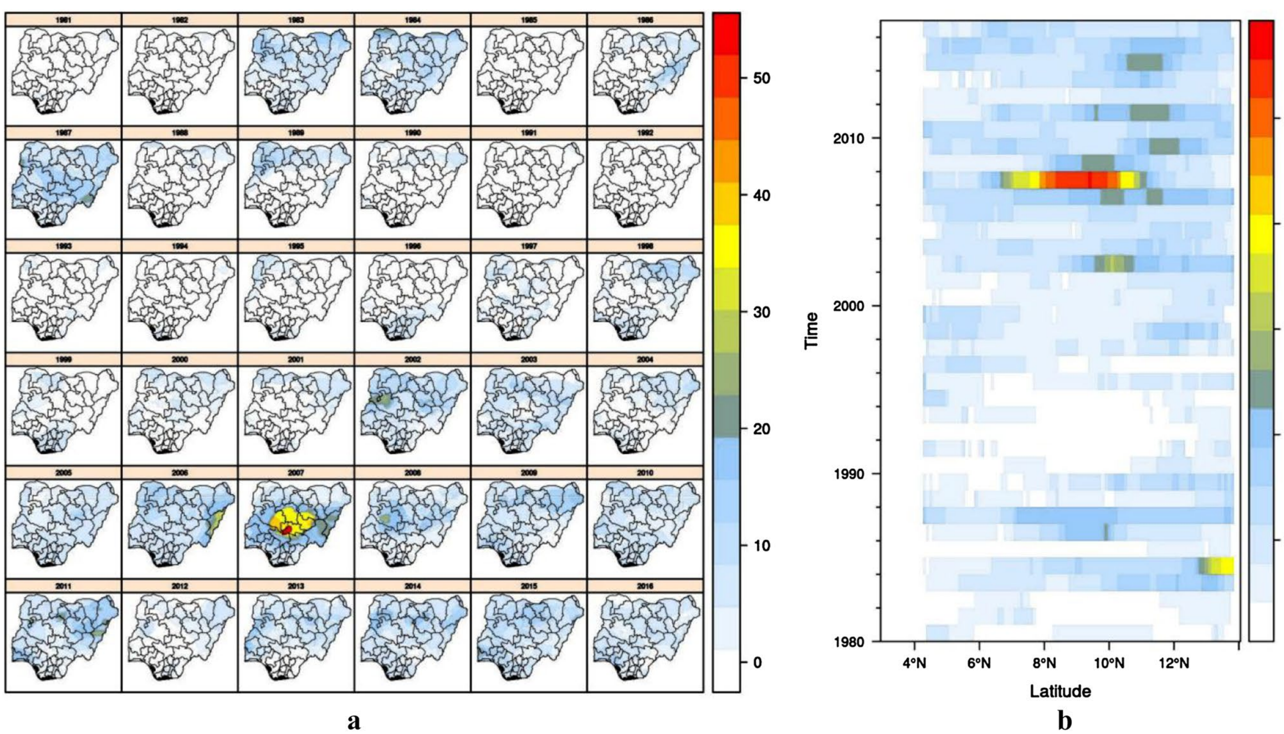


Fig. 5 Heat Wave Duration (HWD) of Nigeria using EHF: **a** yearly distribution; **b** Hovmöller

the spatial coverage was very small in the state. In 1987 the north and middle part, comprising Zamfara, Kaduna, Kano, Bauchi and Plateau States had 8–13 days that were the longest EHF heat waves. Indeed, the Guinea and Sudan Savannah hardly had 4 days in the 1980s and 1990s till 1996 where the south read 8 days especially in Cross River, parts of Kwara and Rivers States. In 2007, Kogi, Niger and Abuja Federal Capital Territory (FCT) counted 35–50 days and 2008 HW spotted in Minna with 17 days.

This is shown in Fig. 5a. The Hovmöller also showed an increase in the last decades (Fig. 5b).

Heat wave frequency (HWF)

The TX90 recorded a peak of ~ 85 days in 2006 and 2007 in the eastern part of Nigeria covering all Borno and Adamawa States. The years 1983 and 1987 reached 45 and 55 days in Borno and Yobe, respectively. From 1996, the Coastal and Tropical Rainforest zones registered 10–15 days in Cross River, Bayelsa, Rivers and Delta. Niger state experienced in 2002, 45 days of heat wave. From 2007, the frequency has been increasing with an average of 30 days except for 2012 where it was low. The frequency shows the same pattern of increase in the last decades (see Fig. 6a).

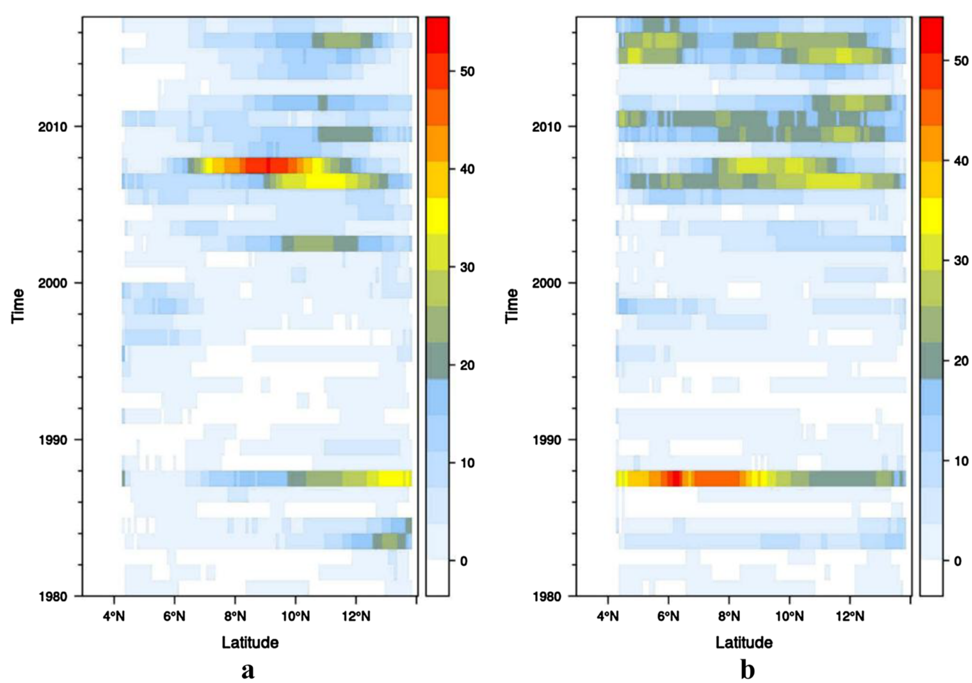
Taking into account a possible correlation between the maximum and minimum temperature, the results with HWF for TX90 are similar to the ones of HWF for TN90. Effectively, peaks of 38 and 55 days have, respectively, been observed in 1983 in the Sahel (Borno State) and in 1987 from the Coastal to Tropical Rainforest covering part of Guinea Savannah in Cross River, Osun, Ekiti, Edo, Delta and Benue States. A 70-day frequency has been observed in 2006 and 2007 in the Guinea and Sudan Savannah zones in the east, covering Bauchi, Gombe, Adamawa and the southern part of Borno and also in the west of Sahel reckoning Zamfara and Sokoto States. The Sahel was overwhelmed by a 38-day heat wave in 2011 and a 40–50 day heat wave in 2014. For TN90, the frequency has also increased similarly to the TX90 in the Hovmöller plot (Fig. 6b).

There is a spatial increase in the highest values of HWF in Nigeria from 2005. The EHF shows in Fig. 10a the same results with the TX90 and the TN90. In 1983 and 1987, the frequency reached 50–70 days in the extreme north east and 45–50 days in all the climatic zones, respectively. The period 2005–2010 had the highest HWF in the east (Adamawa and Borno States). The years 2006 and 2007 observed the highest HWF of the whole period with frequencies reaching 100 days in the eastern part of Guinea and Sudan Savannah. Figure 7a shows an increase in the frequency of heat waves (using the EHF) and presents higher values compared to the TX90 and TN90. Figure 7b summarises the changes in the frequencies of EHF in the country.

Heat wave magnitude (HWM) and heat wave amplitude (HWA)

The 1980s had an average heat wave of magnitude 35 °C and 45 °C which was the general peak in the Sahel for the considered period with TX90. In 1985, the occurrence of heat wave was spatially small and found only in Kebbi and Yobe States while the amplitude in the same year was almost the same value as the magnitude, 30–45 °C. In the 1990s, heat waves were 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 heat waves during the 1990s, but the Coastal and Tropical Rainforest zones had some lower magnitude of 25–30 °C. In the Sahel, the heat waves were observed more in the south east of the zone. From 2002 the coverage of heat waves was extended to all the country, but the amplitude and magnitude follow the

Fig. 6 Heat Wave Frequency (HWF) of Nigeria, Hovmöller: **a** TX90 **b** TN90



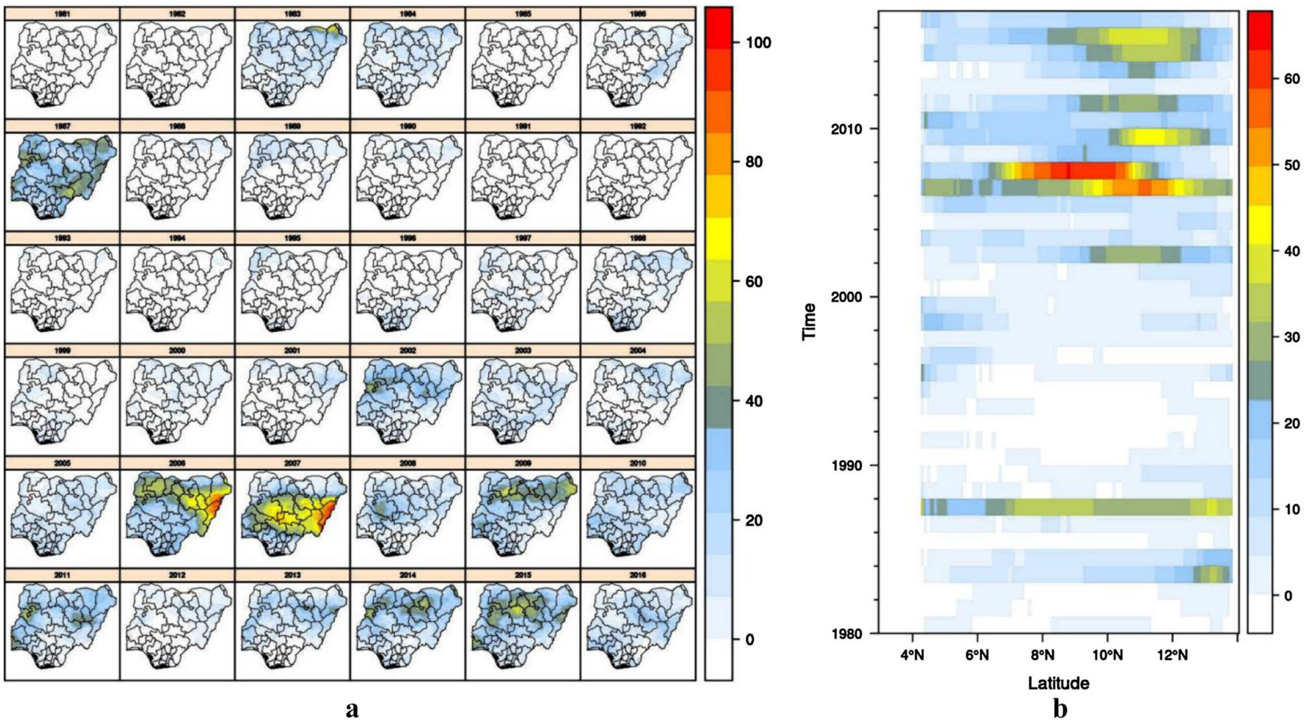


Fig. 7 Heat Wave Frequency (HWF) of Nigeria using EHF: **a** yearly distribution; **b** Hovmöller

same pattern as the temperature. The Sahel had the highest magnitude and amplitude superseded by the Sudan Savannah, Guinea Savannah, Tropical Rainforest and the Coastal zone came last. The same pattern was observed during the latest years 2007–2016. A variation in the spatial coverage of heat waves of amplitude and magnitude 35 to 40 °C was observed, but there is no clear increasing trend. The northern part of the country, mainly the Sudan Savannah and the Sahel, were affected by high magnitudes and amplitudes (Fig. 8a, b for the magnitude and Fig. 10a for the Hovmöller plot) and from 2000 the whole country was covered by a 30 °C temperature.

The magnitude and amplitude of TN90 shows the same pattern over the years, but they are lower than the ones observed in TX90. This is normal if we assume that there is a correlation between the TX and TN and always TX > TN (see Figs. 9a, 10b).

The HWM for EHF is slightly similar to the HWM for TX90. As shown in Fig. 9b, the high magnitudes are mainly located in the Sahel and there was an increase in the magnitude 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 heat wave was severe in the eastern part of the Sahel (8–11 $°C^2$), and the rest of the country experienced heat waves of average magnitude 4 $°C^2$. In 1987, the country was overwhelmed by an average HWM of 7–11 $°C^2$, where the peak (11 $°C^2$) was found in Benoue State in the Guinea Savannah. Then 2002, 2006, 2007, 2009, 2011, 2014 and 2015 recorded high HWM principally in the Sudan Savannah, the Sahel at the eastern parts of Nigeria. The years 1987, 2006 and 2007 had the highest records of HWM in the present time. The amplitudes are shown in Fig. 10c. The aerial coverage of the amplitude and magnitude has increased over the year.

The HWM results obtained in this analysis (see Fig. 11) were compared to another robust index that is the Heat Wave Magnitude Index daily (HWMId). The HWMId is the highest annual magnitude of heat waves. The heat wave occurrence has a different pattern compared with this index. The results displayed a general overview of HWMId in Nigeria from 1981 to 2016. The general magnitude of TX in Fig. 11a, b, varies from 1 to 30, from normal to super extreme heat waves. The period 1981–1986 revealed an extreme heat wave (magnitude = 5) all over the country with a super extreme heat wave (magnitude = 17) in Cross River State in the Coastal zone in 1983. Cross River in the south east experienced a Super extreme heat wave of magnitude 25 in 1990 and Ebonyi, Enugu, Delta and Bayelsa States followed with Super extreme heat waves. The Guinea and Sudan zones were more affected by heat waves than the Sahel. Only the period 2002–2010 had shown extreme (magnitude 5–8) heat waves in the Sahel, and they were located, many of them, in the east of the country. The recent years

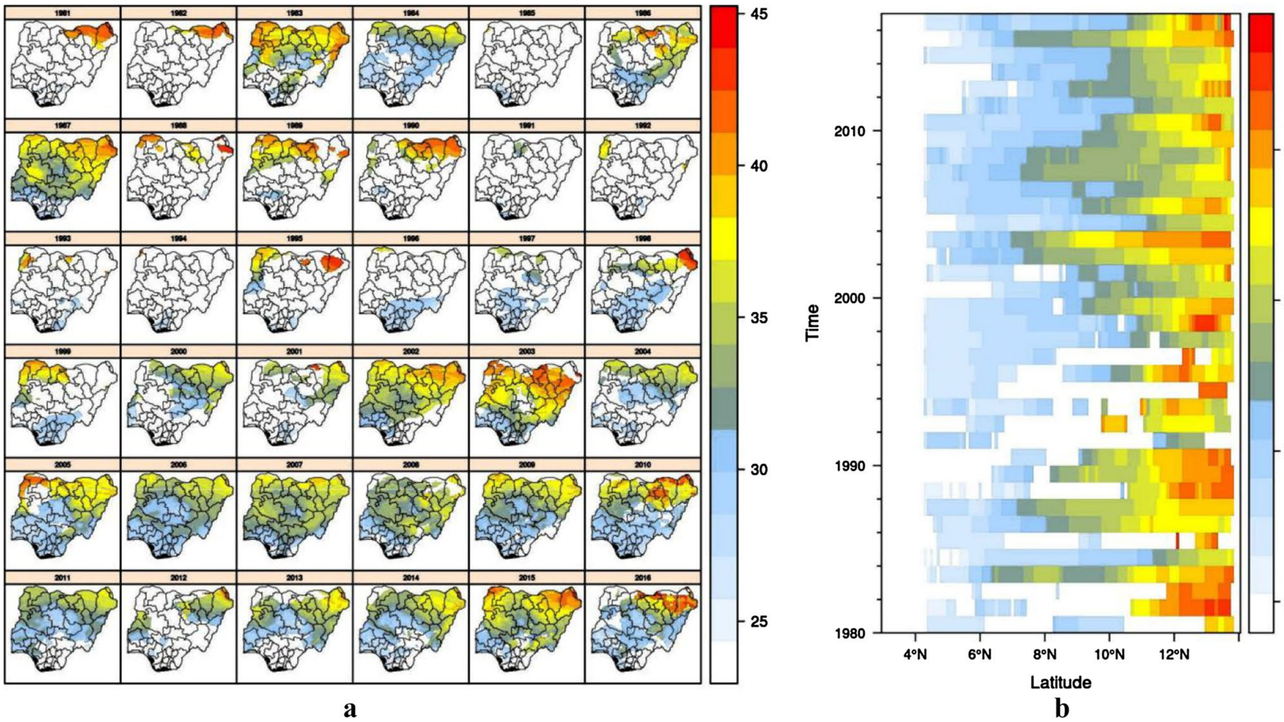


Fig. 8 Heat Wave Magnitude (HWM) of Nigeria using TX90: **a** yearly distribution; **b** Hovmöller

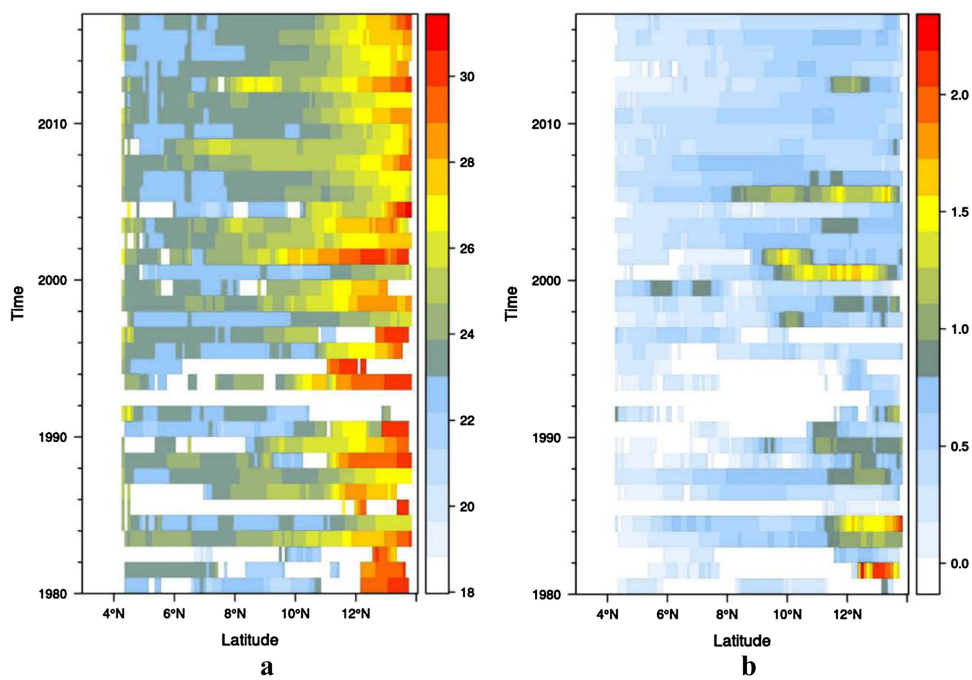


Fig. 9 Heat Wave Magnitude (HWM) of Nigeria, Hovmöller: **a** TN90 **b** EHF

2011–2016 revealed magnitudes generally with peaks of 15 (very extreme) in the South (Akwa-Ibom, Enugu, Ebonyi, Abia and Imo States).

The HWMId on TN (see Fig. 11c, d) is slightly different from the TX. The magnitude of heat waves is lower and affected to a greater extent the Coastal, Tropical Rainforest and the Savannah zones with super extreme heat wave events in 1998 affecting principally Kogi, Nassarawa, Abuja FCT States and also Niger and Ondo States. The Sahel is less affected by severe heat waves. In 2007, Niger State was particularly affected by a very extreme heat wave. This looks particular because only Niger State was affected by such

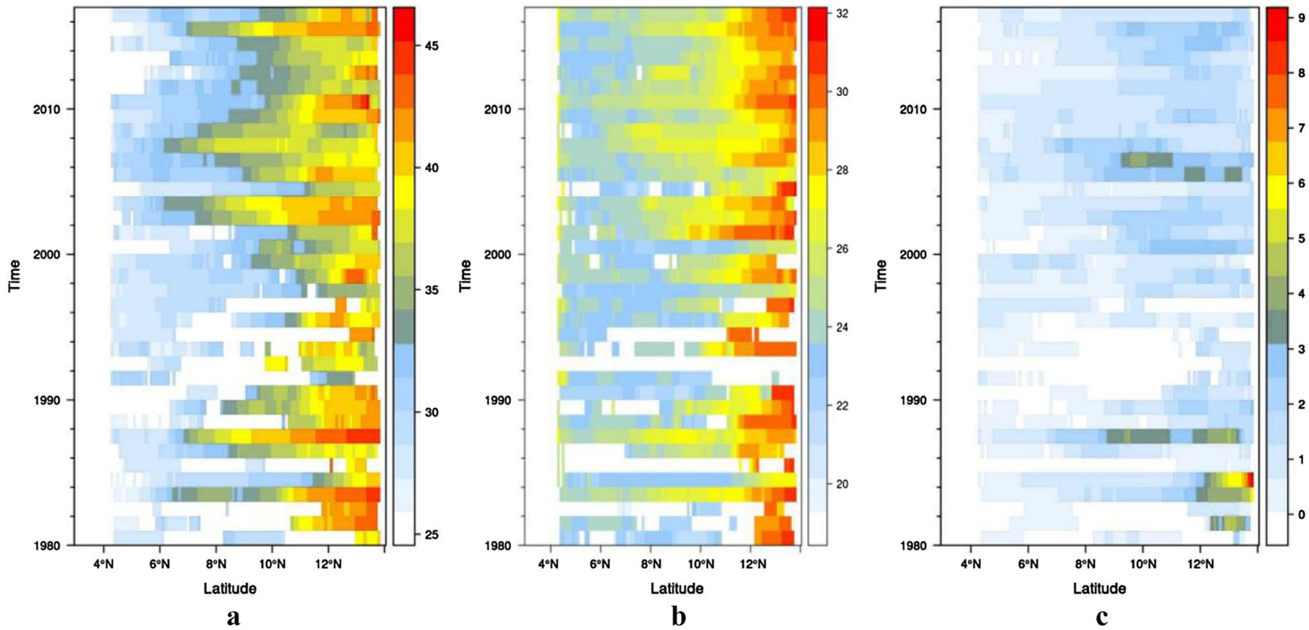


Fig. 10 Heat Wave Amplitude (HWA), Hovmöller: **a** TX90 **b** TN90 **c** EHF

an intense heat wave in 2007. In 2010 Ekiti was struck by a super extreme heat wave and Kwara, Osun, Oyo, Ondo, Edo, Kogi, Ebonyi and Enugu States had a very extreme heat wave. In 2016 that is the last year of the period, only the Coastal zone was affected by a very extreme heat wave (of magnitude 15). The year 2016 has been declared the hottest year (Schmidt and Arndt 2017). The Hovmöller plots of HWMId showed an increase in the aerial coverage from 2000 and the magnitude seems to increase in many zones such as Tropical Rainforest, Guinea and Sudan Savannah.

The study shows that heat waves occurred in Nigeria from 1981 to 2016 and almost every year. The occurred heat waves have number of events, duration, frequency, amplitude and magnitude that are the characteristics/aspects of heat waves. The three definitions (TX90, TN90 and EHF) showed in many cases the same pattern revealing a relationship between 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 heat waves without following the spatial trend of temperature in Nigeria. These results fall out in the same occurrence of heat waves in selected stations (Lokoja, Minna, Kano, Sokoto and Maiduguri) across Nigeria (Balogun et al. 2016) for heat wave 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 heat waves in mainly 1983, 1987, 1999 and 2005 and the principal site of heat waves was the upper zones especially the Sahel.

The Hovmöller plots revealed an increase in the changes over time and in aerial coverage for almost all the characteristics of heat waves in the different climatic zones of Nigeria. In Nigeria like in the West African countries, the Inter-Tropical Convergence Zone (ITCZ) is at the origin of the fluctuations in the weather and climate. During the months from May to August the ITCZ is located around 22°N causing increasing heat in the covered regions. The heat in the tropics are mainly related to increasing temperature and to humidity in some regions in West Africa (Adeniyi et al. 2017). The northern part of Nigeria also classified as a semi-arid region with the Sahelian zone, could experience the decline of the soil moisture reducing the rate of latent heat flow and causing the air to rise furthermore (Horton et al. 2016). Therefore, the rise and stagnation of the hot air over the area is at the origin of the observed heat events. The climate of Nigeria is affected by climate change and the changes are mainly observed in the temperature (Ragatoa et al. 2018a). The increase in the temperature easily leads to the increase in extreme events like hottest days and hottest nights and mainly heat waves (Easterling et al. 2000). The 1980s heat waves occurred at the same time as the drought that affected the whole west Africa, especially the Savannah zones and the Sahel due to the changes in the patterns of the sea surface temperature (SST), a natural process inherited from the general warming of the oceans (Giannini 2007). Through the analysis, it is noticed that the climate is changing in Nigeria and the temperature extremes have increased in frequency. Heat waves have also increased mainly in number of annual events, in duration and frequency. The

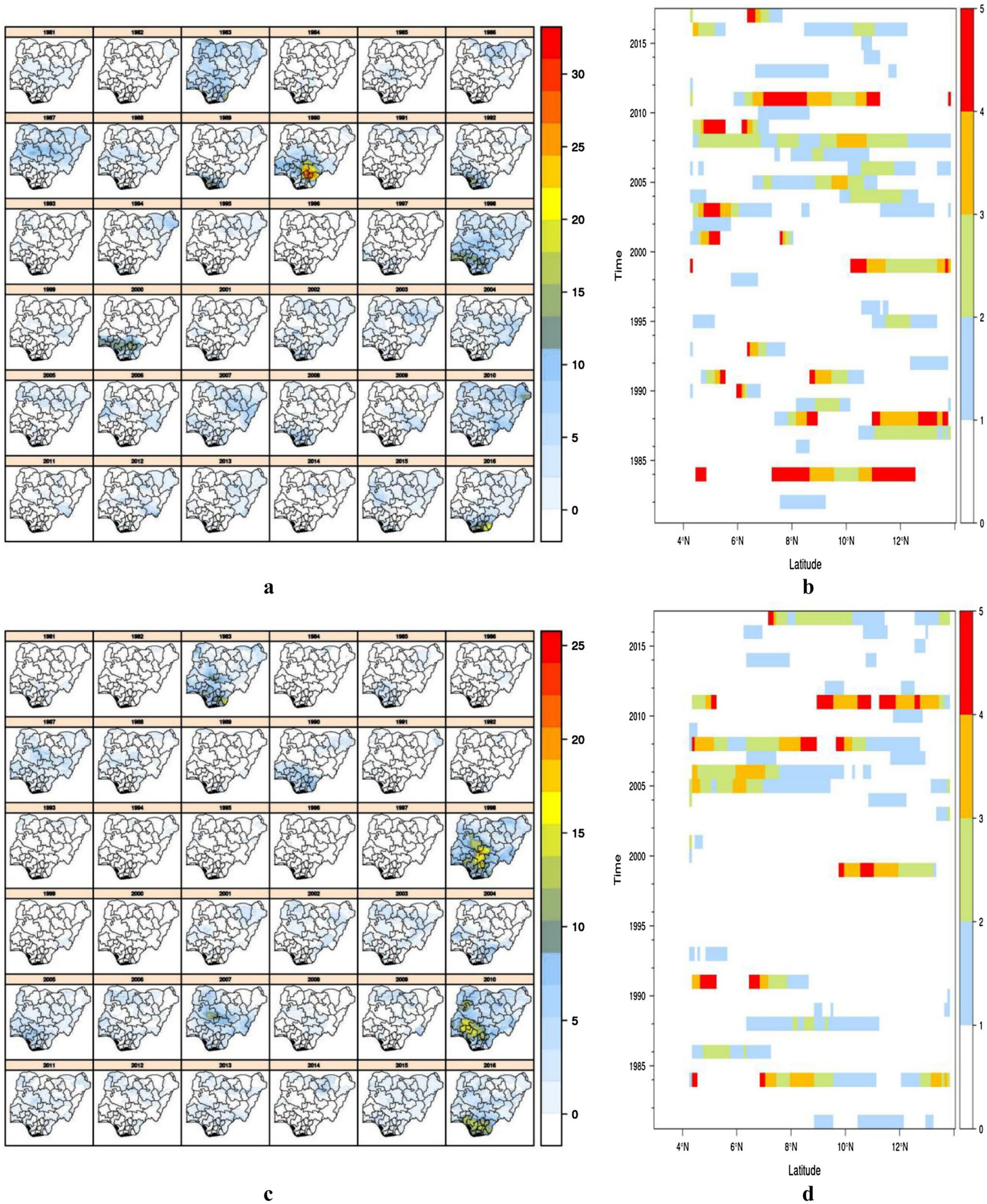


Fig. 11 Heat Wave Magnitude Index daily for minimum temperature (HWMId) of Nigeria: **a** TX yearly distribution; **b** TX Hovmöller; **c** TN yearly distribution; **d** TN Hovmöller

magnitudes have increased very lightly, but heat waves have covered more States in the last decades.

The results of the study follow the conclusion of Ceccherini et al. (2016b) and Russo et al. (2016) who studied heat waves in the whole of Africa. There is an increase of heat waves in the last past 10 years. Moreover, this increase will continue under climate change conditions and projected scenarios (Ragatoa et al. 2018b). The occurred HWMId in 1990 of magnitude 32 (in the Tropical Rainforest) in Nigeria can be compared to all the heat waves preceding the European summer published in the Guardian, 29 August 2003 that killed 11,000 people and also to the European Summer. The European summer's highest HWMId was 24–36 (Russo et al. 2015) while the highest peak of Nigerian HWMIdtx was 32 in Ebonyi and Enugu States in 1990 and 20 in the Coastal east zone in 2016. But none of them can be compared to the Russian 2010 heat wave published in The New York Times, on July 19 2010, that wilted crops (Russo et al. 2015).

Among the different studied indices, it shows that the agriculture is affected by the different heat waves occurrences. The sector of relevance to each index is indicated as determined by the ET-SCI in consultation with sector representatives, where the five studied indices highly affect agriculture and food security in the country (Ajetomobi 2015, 2016). An increase of the heat wave occurrence and frequency or magnitude in the future years will certainly cause enormous damages to the agricultural sector of Nigeria. Therefore, policies need to be taken. The important heat wave aspects to be carefully monitored should be the HWD, the HWF and the HWM because an increasing frequency and duration of heat waves will affect more the agriculture exacerbating plants' heat stress knowing that heat waves could be accompanied with drought. An increasing magnitude will definitely increase the exposure risk. 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). If exposure is prolonged (HWD), 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.

The results were presented at a yearly scale based on 3 or more consecutive days and could be developed further more at a monthly scale to determine the months that are more affected in the year and by that the period and the agricultural production that will seriously be impacted; this could also lead to determine the germination stage at which each production will have to bear the more.

The Mann–Kendall test applied on the heat wave different characteristics were averaged to determine the mean trend and the statistical significance (p value where alpha = 0.05). Table 3 shows the central values of the Mann–Kendall test on the different heat wave characteristics in Nigeria. The HWN revealed a majority of statistically significant trend (tau is positive with the S statistic and the p value is lower than 0.05 for the TN90 and the EHF). Negative but not statistically significant trends were recorded for HWD TX90, HWA TX90, HWA EHF, HWM TX90 and HWM EHF. Many characteristics showed positive trends but non-significant. The HWMId also shows a positive trend but non-significant. The non-significance of most of the results is highly due to the centralisation of the data in a mean value that is used to represent the results of the test.

Conclusions

This study looked at the occurrence of heat waves and their characteristics/aspects in the whole of Nigeria considering the present time. The 11 km ERA-INTERIM data were used to detect the spatial coverage and occurrence of heat wave characteristics in the present time with three definitions, the 90th percentile of daily maximum temperature TX90, the 90th percentile of daily minimum temperature TN90 and the Excess Heat Factor (EHF), all based on temperature records. The analysis demonstrated that heat waves occurred in Nigeria during the 1980s and increased during the twenty-first 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 heat waves has significantly increased in spatial coverage, but the records were kept at 45 °C (TX90), 32 °C (TN90) and from 8 to 10 °C^2 for EHF. The magnitude (HWM) that is an important measure of heat wave 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. The HWMId displayed a different pattern. There was no perceptible increase in the magnitudes and the spatial coverage on maximum temperature (HWMIDtx), but an increase was observed both in the magnitudes and the spatial coverage of the heat waves and on the minimum temperature (HWMIDtn). This study reveals heat wave events that could seriously affect the agricultural sector of the country and will affect the economy of the country with the increasing population. This implies that the agricultural production will decrease and lead to an eventual

Table 3 Heat wave non-parametric Mann–Kendall test on heat wave characteristics (centralised values)

Indices	tau	*p* value	S	D	varS
Heat wave number (HWN)					
hwn_tx90	0.331573	*0.089766*	95.394640	285.092500	2550.373000
hwn_tn90	0.418286	0.007145	122.142800	291.495200	2613.776000
hwn_ehf	0.418876	0.011313	124.497700	296.548800	2676.419000
Heat wave duration (HWD)					
hwd_tx90	− 0.02903536	*0.53727821*	− 1.750052	77.53703201	393.1825185
hwd_tn90	0.1288547	*0.4123411*	11.78524	81.9421314	416.1373126
hwd_ehf	0.08967655	*0.46230715*	9.67370242	102.2393232	563.5367571
Heat wave frequency (HWF)					
hwf_tx90	0.308964	*0.108421*	91.033778	292.617698	2583.197217
hwf_tn90	0.407359	0.007408	121.458400	297.631100	2638.887000
hwf_ehf	0.393312	0.015148	120.087300	305.161500	2712.883000
Heat wave amplitude (HWA)					
hwa_tx90	− 0.006259111	*0.495935884*	− 1.327589786	87.16181282	430.4181008
hwa_tn90	0.08056816	*0.54034867*	7.4885189	91.39040122	451.158947
hwa_ehf	− 0.01560492	*0.53403424*	− 1.53808763	108.4673646	583.0800677
Heat wave magnitude (HWM)					
hwm_tx90	− 0.050019	*0.457662*	− 5.889403	87.164189	430.422846
hwm_tn90	0.000866	*0.562040*	− 0.093436	91.397190	451.172500
hwm_ehf	− 0.123825	*0.396932*	− 13.728145	108.467365	583.080068
Heat wave magnitude index daily (HWMId)					
hwmidtn	0.1967785	*0.222684*	53.789695	272.574315	2302.164493
hwmidtx	0.056734	*0.530766*	16.661450	281.578500	2411.911000

Italic values indicate the statistically non significant trends (*p*-value > 0.05)

Tau is the Kendall's tau statistic, *p* value is the two sided probability value, *S* is the Kendall score, *D* is the denominator where tau = S/D, *varS* is the variance of S

food crisis. The electricity domain will be struck by the destruction of the infrastructures and lead to a greater pollution by the use of generators that are already used by the population in many States. The destruction of electric infrastructures will affect the power supply and the population will face difficulties to conserve their foods and goods, and this will still contribute to food crisis because of the damages. This study can lead to other works to determine the future behaviour of heat waves and their sectoral impacts in Nigeria like the agriculture, health and infrastructure sectors.

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