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Spatio-temporal Assessment of Heat Waves in different Climate Zones of Nigeria

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ABSTRACT: This study examines spatial and temporal heat wave characteristics in Nigeria using the Köppen climate classification system (KCCS). It analyzes the Heat Wave Duration Index (HWDI) and Heat Wave per Time (HWPT) for six major KCCS: Af (Tropical rainforest climate), Am (Tropical monsoon climate), Aw (Tropical savanna climate), Bsh (Hot semi-arid climate), Bwh (Hot desert climate), and Csh (Cold semi-arid climate). The data from 2010 to 2022 was obtained from the European Center for Medium Range Weather Forecast version-5 Reanalysis (ERA5) data sets. The results reveal distinct variations in HWDI/HWPT values across climate categories. The Af, Am, Aw and Csh classes exhibit positive regression coefficients, indicating a rising trend in HWDI/HWPT per year. In contrast, the Bsh and Bwh classes have negative regression coefficients, suggesting a decreasing trend in HWDI. The monthly distribution of HWDI and HWPT shows varying patterns across climate classes. Higher values of HWDI and HWPT are observed in specific months (especially dry season months), reflecting the seasonal variability of heat waves. The spatial distribution analysis highlights areas with high HWDI/HWPT values, such as Bauchi, Borno, Kano, Jigawa, and Katsina from November to May. The study also investigates the impact of land cover types on heat wave characteristics, with different land cover classes contributing varied percentages of heat wave occurrence, with barelands having the highest heat wave occurrence. The findings emphasize the importance of considering KCCS when assessing heat waves and provide valuable insights for developing targeted adaptation strategies to mitigate the impacts of heat waves in specific regions.

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A heat wave is a moment of extreme hot weather that may go together with high humidity in a location for two or more days (Meehl, 2004). Heat waves are measured in comparison with the normal climate of an area and the usual temperatures of the season. Temperatures from a hot climate considered to be normal can be termed heat waves in cooler regions if they are beyond the normal pattern for that area (Robinson, 2001). Heat waves are the effect of trapped air. Naturally, air circulates round the world in large prevailing winds. Nevertheless, when trapped over a region it becomes warm to abnormal temperatures as a result of sunshine. Trapping of air is caused by high-pressure systems that force the air downwards, thereby acting as a large cap and the trapped air is unable to rise into the cooler upper atmosphere, thus preventing precipitation (Lau and Nath, 2012). Heat waves can cause a rise in the health and emergency services and increase demand on water, energy and transportation leading to power shortages or blackouts. Food safety and the general well-being of humans may also be strained with lose of crops or animals as a result of excessive heat (Troy *et al.*, 2015). When the physiological ability of the human body to handle increase in temperature is exceeded, the dangers of functional failure, disease aggravation and even death may arise. If the temperature of the body increases beyond 38°C, physical and mental functions are weakened and beyond 40.6°C the risks of organ impairment, loss of consciousness and mortality rises abruptly. At higher temperatures, the movement of blood to the body

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surface could result to circulatory failure (Agan, 2017). Heat waves can be very dangerous especially when the people are unaware and not prepared. Heat waves caused the death of about 70,000 people in Europe in 2003 (Garcia-Herrera *et al*., 2010) and 55,000 people in Russia in 2010 (Aditya, *et al*., 2021). In Nigeria, more than 60 people died as a result of heat wave which continued for three days in Maiduguri (Agada and Yakubu, 2022). The dangers of excessive heat or heat waves are mostly overlooked and, usually misrepresented, particularly in developing countries like Nigeria. Extreme heat has been affecting especially the Northeastern part of Nigeria in the past decade, but the effects are mostly unreported because of the lack of awareness. The most known cause of heat wave death are cardiovascular, respiratory and cerebrovascular diseases (Basu, 2015). Gobir, *et al* conducted a study to assess the knowledge of heat waves and the practice of protective measures against it in an affected rural community of Nigeria, the results showed that 89.4% of the respondents had poor knowledge of heat waves (Gobir *et al*., 2020). Agan asserted that heat waves are experienced round the world and countries in temperate regions of Europe and Asia especially France, Germany China, India etc. have studied extensively and have ongoing researches on its occurrence and impact while Nigeria is far behind on the important subject for research. He emphasized the need for more studies on the link between heat waves and health as it affects the entirety of the human race (Agan, 2017). Agada and Yakubu investigated the impact of heat waves in Yobe State, northeast Nigeria using temperature and humidity data of thirty years (1991-2020) for the hot season (March-June) obtained from the Nigerian Meteorological Agency (NiMet) Abuja. The study revealed a positive temperature trend and an average maximum temperature anomaly, indicating that the intensity of heat waves will rise in the future due to global warming caused by the continuous emission of greenhouse gases (Agada and Yakubu, 2022). Ragatoa *et al*. investigated heat wave characteristics [number (HWN), duration (HWD), frequency (HWF), amplitude (HWA) and magnitude (HWM)] in different climatic zones (Coastal, Tropical Rainforest, Guinea Savannah, Sudan Savannah and the Sahel) of Nigeria over a long period using ERA-INTERIM reanalysis daily minimum and maximum temperature data from 1981 to 2016 obtained from ECMWF data base and concluded that HWs occurred and covered more zones within the study period (Ragatoa *et al*., 2018). The Sahel had the highest number of HW events and the highest number of days for the duration and frequency. They used the heat waves magnitude index daily (HWMId) to calculate and compare the intensity of heat waves in contemporary time and the results showed super extreme heat waves (HWMId > 32) in the Sahel region and extreme heat waves in the coastal region (south) (Ragatoa *et al*., 2019). Agu, *et al*., examined the impact of heat wave within Enugu city, and found that the land surface temperature (LST) increased over the years and more than 50% of the people felt discomfort (Agu *et al*, 2020). Hence, this study employed the Köppen Climate Classification System to evaluate the Spatiotemporal Assessment of Heat Waves in different climate zones of Nigeria.

MATERIALS AND METHODS

Study area: Nigeria is a country situated in Africa and made up of 36 states and the Federal Capital Territory (Abuja). The nation is the most densely populated area of West Africa, located in between the dry Sahel and desert to the north and the Atlantic Ocean to the south. Geographically, Nigeria is located at between attitudes 4° – 14°N and longitude 2°W – 14°East and covers an area of about 923,769 km^2. The vegetation zones comprise; forest, guinea, Sudan and Sahel savannah. The country has two basic rivers; the Benue and Niger rivers with a network of many others and most settlements are at the banks of some rivers or streams. The precipitation distribution in the forest and guinea savannah regions is higher than the dry Sahel (Abiem *et al*., 2020). Figure 1 is the geographical map of Nigeria, showing the 36 states and FCT, while Figure 2 is the geographical map showing the different climate zones.

Fig 1: Maps of Nigeria showing 36 states

Data: The data used in this work was obtained from European Center for Medium Range Weather Forecast version-5 Reanalysis (ERA5) data sets. The data was obtained from https://cds.climate.copernicus.eu/cdsapp#!/dataset.

The heat waves were studied in the various Koppen climate classifications. The Köppen climate classification system is a widely used method of classifying climates based on temperature, precipitation, and vegetation (Kottek *et al*., 2006). The six main Köppen climate classifications that are mentioned include: Af (Tropical rainforest climate), Am (Tropical monsoon climate), Aw (Tropical savanna climate), Bwh (Hot desert climate), Bsh (Hot semi-arid climate) and Csh (Cold semi-arid climate). The Land cover data by European Space Agency (ESA) Climate change Initiative (CCI) was used to study the heat waves in the various land cover classes classified as: Croplands, Herbaceous, Shrubland, Natural vegetion, Tree cover, Sbrubs+Herbs, Grassland, Urban, Bare and Water.

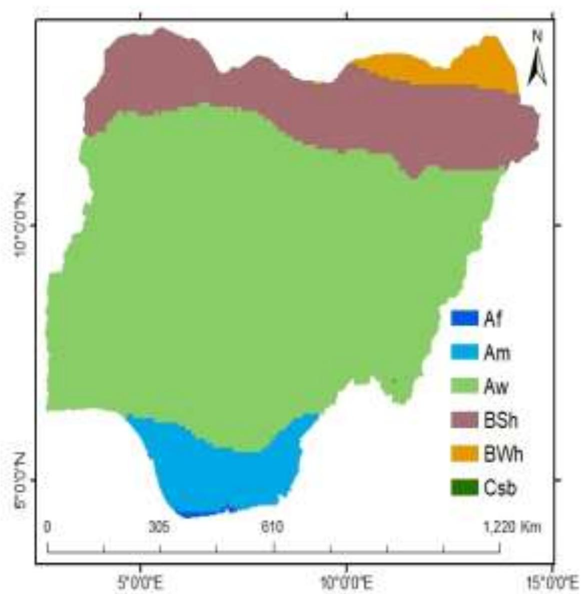

Fig 2: Map of Nigeria showing different climate zones (Kottek *et al*., 2006).

Methods: The heat wave characteristics analyzed in this work is the Heat Wave Duration Index (HWDI) and Heat Wave per Time (HWPT) using the data obtained from the eca_hwdi algorithm in climate data operators. The methods include: (1) Determination of Maximum temperature records: Maximum temperature records from 2010 to 2022 were used for this work, (2) Determination of mean maximum temperature: For each day of the reference period, the mean maximum temperature was computed. For each calendar day, the temperatures from all years within the reference period were averaged, (3) Determination of the threshold temperature: A 90th percentile threshold of the daily maximum temperature was used to determine the temperature above which a heat wave is considered to occur. A heat wave threshold, for example, could be specified as the 90th percentile of temperatures within the reference period, (4) Identification of heat wave events: The heat wave events were compared with the set threshold (90th percentile of daily maximum temperatures) and a heat wave was described as a series of days with temperatures exceeding the threshold, and (5) Calculation of the Heat Wave Duration Index (HWDI). The HWDI was computed by adding the lengths of all detected heat wave occurrences in the dataset and dividing the total by the length of the reference period. The result indicates a value that represents the proportion of time spent in heat wave conditions relative to the reference period. The HWPT is thus the number of heat waves per time.

RESULTS AND DISCUSSION

Annual and Seasonal distribution of heat waves: Figure 3a and 3b, shows annual trends in HWDI and HWPT. Results show that, in the Af climate class, the regression coefficient for HWDI is 0.0113/yr. In the Am climate class, the HWDI shows a much higher positive regression coefficient of 0.7899/yr. This suggests a stronger relationship between the independent variable and HWDI compared to the Af class. Similarly, the AW climate class also exhibits a high positive regression coefficient for HWDI, with a value of 0.8204/yr. This implies a significant increase in HWDI per unit increase in the independent variable. In contrast, the HWDI regression coefficients for the Bsh and Bwh climate classes are negative. The coefficient for the Bsh class is -2.1791/yr, demonstrating a declining trend in HWDI with the independent variable. The coefficient for the Bwh class is considerably lower, at -3.7041/yr, indicating a greater fall in HWDI over time or other pertinent factors. Finally, the positive regression coefficient of 1.2665/yr for the Csh climatic class indicates a rising trend in HWDI with the independent variable. Furthermore, the regression coefficient for HWPT in the Af climatic class is 0.0015/yr, which is substantially smaller than the comparable coefficient for HWDI in the same class. This shows that the independent variable has a lesser association with HWPT than with HWDI. When compared to the Af climate class, the Am and Aw climate classes both have larger positive regression coefficients for HWPT. The coefficient for the Am class is 0.1205/yr, whereas the value for the Aw class is 0.1926/yr. The Bsh and Bwh climate classes had negative regression coefficients for HWPT, which is consistent with the pattern reported in these classes for HWDI.

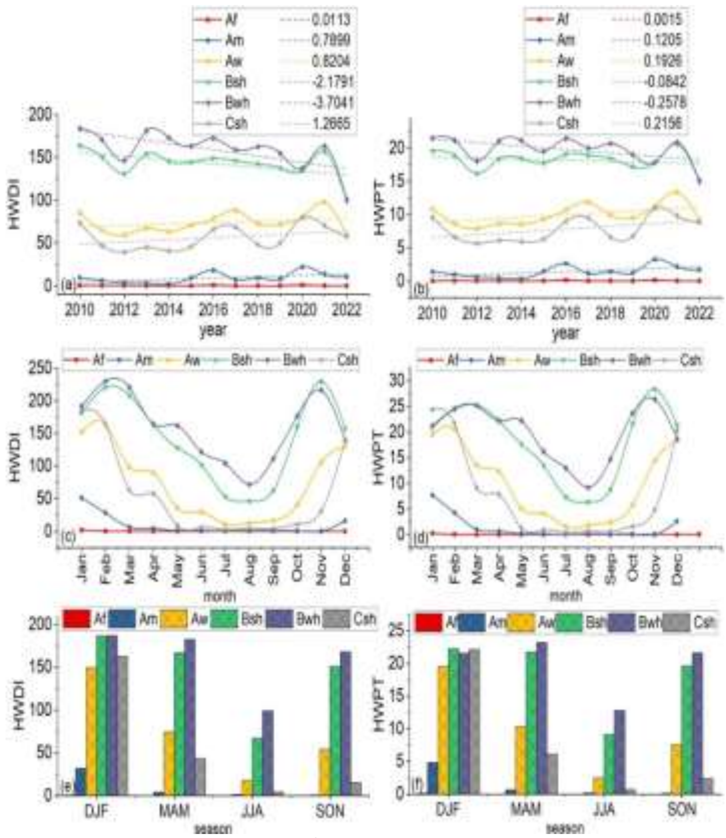

Fig 3 (a) and (b) Annual distribution of HDWI and HWPT respectively across the climate zones. (c) and (d) Monthly distribution of HDWI and HWPT respectively across the climate zones. (e) and (f) seasonal HDWI and HWPT respectively across the climate zones

Table 1 Monthly values of HWDI and HWPT

	Af	Am	Aw	Bsh	Bwh	Csh
HWDI						
Jan	0	9	85	164	184	74
Feb	0	6	64	150	170	47
Mar	0	4	59	131	146	39
Apr	0	3	67	154	181	45
May	0	2	63	145	173	41
Jun	0	9	71	144	163	46
Jul	1	18	78	149	172	66
Aug	0	7	88	146	159	68
Sep	0	9	73	143	162	48
Oct	0	8	72	138	155	50
Nov	1	22	81	135	137	80
Dec	0	14	97	157	163	70
HWPT						
	Af	Am	Aw	Bsh	Bwh	Csh
Jan	0	1	11	20	21	10
Feb	0	1	9	19	21	7
Mar	0	1	8	16	18	6
Apr	0	0	9	18	21	6
May	0	0	9	18	21	6
Jun	0	1	9	18	19	6
Jul	0	3	11	19	21	9
Aug	0	1	12	19	20	9
Sep	0	1	10	18	21	7
Oct	0	1	10	17	19	7
Nov	0	3	11	18	18	11
Dec	0	2	13	21	21	10

The coefficient for the Bsh class is -0.0842/yr, whereas the coefficient for the Bwh class is -0.2578/yr. In these climate classes, this implies a declining trend in HWPT with the independent variable. The Csh climate class has a positive regression coefficient for HWPT of 0.2156/yr, showing that HWPT is growing with the independent variable. Figure 3(c and d) shows the monthly distribution of HWDI and HWPT across the climate classes. The results show that, in the Af climate class, the HWDI values range from 0 to 1, with higher values observed in the months of July (1) and November (1). The HWDI values in the Am climate class vary from 2 to 22, with the highest values observed in November (22) and the lowest in April (3) and May (2). HWDI values in the Aw climate class range from 59 to 97, with December having the highest value (97) and March having the lowest (59). HWDI values in the Bsh climate class range from 99 to 164, with January having the highest value (164) and November having the lowest (135). The HWDI values in the Bwh climate class range from 101 to 184, with the highest values in January (184) and the lowest in November (137). HWDI values in the Csh climate class range from 39 to 80, with the highest values in November (80) and the lowest in March (39). Furthermore, the HWPT values in the Af climate class range from 0 to 3, with the highest values seen in July (3) and the lowest in February (1). HWPT levels in the Am climate class ranged from 1 to 22, with November having the highest value (22) and February having the lowest (1). HWPT values in the Aw climatic class range from 8 to 97, with December having the highest value (97) and March having the lowest (8). The HWPT values in the Bsh climate class range from 15 to 21, with stable levels over most months. HWPT levels in the Bwh climate class range from 15 to 21, with stable values across most months. HWPT levels in the Csh climatic class range from 6 to 11, with stable values over most months (Table 1).

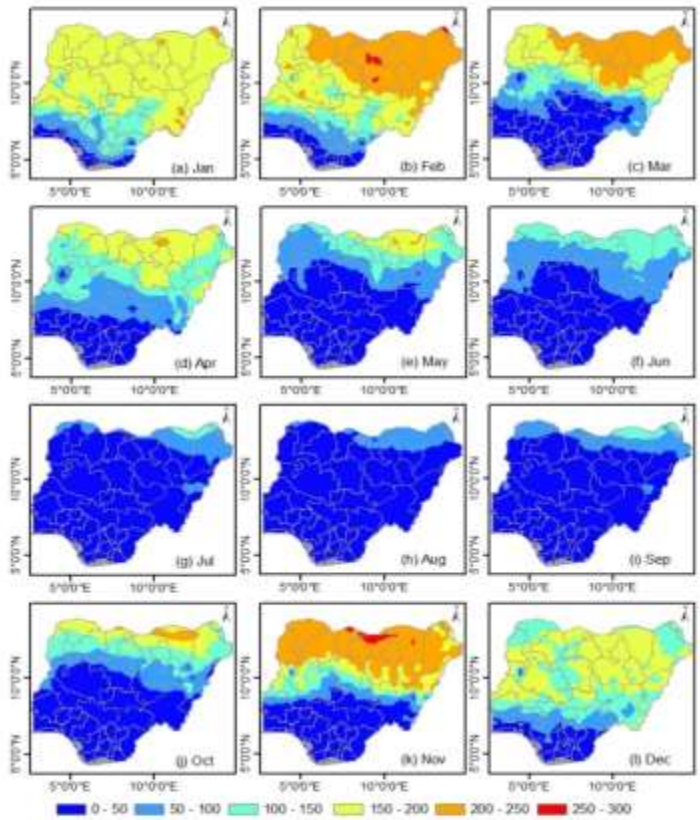

Fig 4 Spatial distribution of HWDI over Nigeria from 2010 to 2022

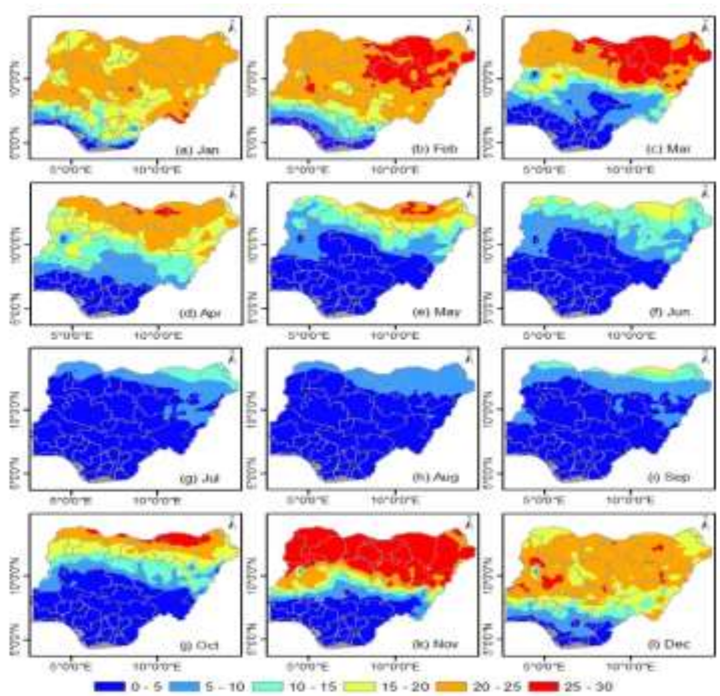

Fig 5 Spatial distribution of HWPT over Nigeria from 2010 to 2022

Figure 3(c and d) shows the seasonal distribution of HWDI and HWPT across the climate classes. Results reveal that, in the Af climate class, the HWDI values for different seasons are consistently low, ranging from 0 in all seasons except DJF, where it reaches 5. The Am climate class shows relatively higher HWDI values, ranging from 1 in MAM to 10 in DJF. The Aw climate class exhibits HWDI values ranging from 2 in JJA to 20 in MAM. In the Bsh climate class, the HWDI values range from 9 in JJA to 22 in DJF. The Bwh climate class shows HWDI values ranging from 13 in JJA to 23 in MAM. The Csh climate class exhibits HWDI values ranging from 1 in JJA to 22 in DJF. Also, in the Af climatic class, the HWPT values for different seasons fluctuate, with DJF having the greatest value of 186 and the other seasons having relatively lower values. HWPT readings in the Am climatic class range from 1 in JJA to 32 in DJF, showing an increase in heat wave frequency over the winter. HWPT scores in the Aw climatic class range from 18 in JJA to 149 in DJF, indicating a considerable rise in heat wave frequency throughout DJF. The HWPT values in the Bsh climatic class vary from 67 in JJA to 186 in DJF, demonstrating a significant increase in heat wave frequency throughout winter. HWPT readings in the Bwh climatic class range from 99 in JJA to 187 in DJF, indicating a significant increase in heat wave frequency throughout winter. HWPT readings in the Csh climatic class range from 4 in JJA to 163 in DJF, indicating an increase in heat wave frequency throughout winter.

Spatial distribution of HWDI and HWPT: Figure 4 and 5 shows the spatial distribution of HWDI and HWPT across the months, averaged from 2010 to 2022. Results show that, in February, high HWDI values (250-300) are found around Bauchi, Borno, Kano, Jigawa, and Katsina (figures 4 and 5). During the month of November, the highest HWDI values are found near Katsina, Kano, Jigawa, and Yobe. Furthermore, the geographical distribution of heat waves per time period (HWPT) indicates high values (25-30) in Kano, Katsina, Jigawa, and Yobe during the months of February and March. Sokoto, Katsina, Jigawa, Yobe, and Borno had high HWPT in September. The month of November has the greatest spatial dispersion of HWPT in the north, reaching down to some states in the north central and south west. In December, the highest HWPT is found in certain states across the country, including Jigawa, Kebbi, Kaduna, Nasarawa, Taraba, Yobe, Kwara, Gombe, and Oyo.

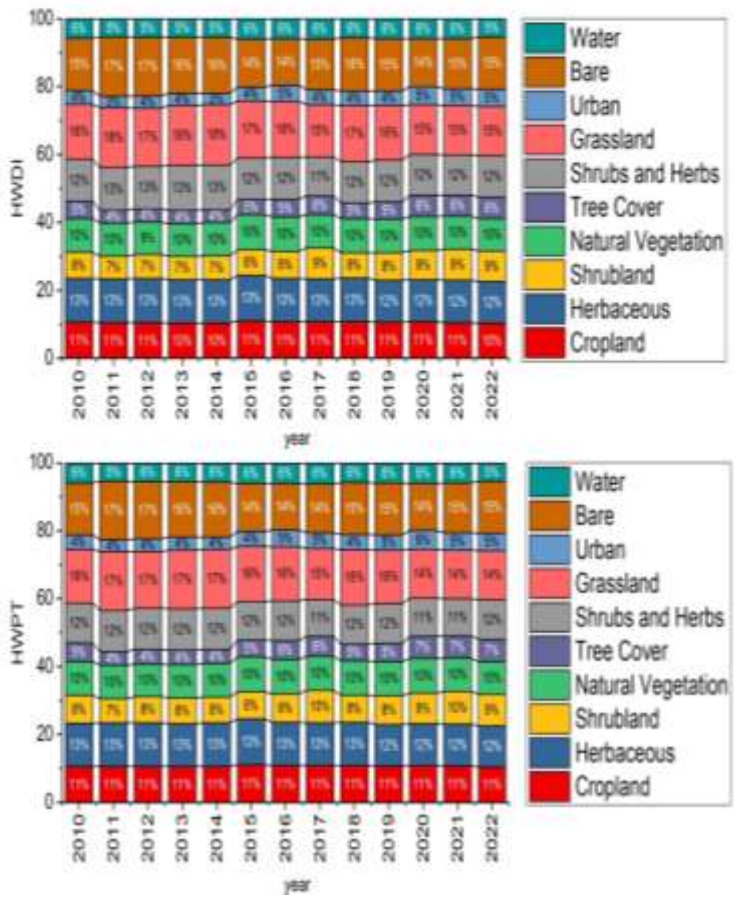

Fig 6 HWDI and HWPT across the land cover classes from 2010 to 2022

HWDI and HWPT in different Land cover classes: Figure 6, shows the HWDI and HWPT across the land cover classes from. Results indicated percentage values of the Heat Wave Duration Index (HWDI) across various land cover classes, providing insights into the duration of heat waves experienced in different areas based on land cover characteristics. It can be observed that Cropland consistently experience 11% to the HWDI, indicating a stable duration of heat waves in these areas. Similarly, the Herbaceous, Shrubs, Natural vegetation, and Tree cover classes exhibit steady percentage values over time (Herbaceous - 13%, Shrubs - 7%, Natural vegetation - 10%, Tree cover - 4%). In contrast, the Urban and Bare land cover classes show some variability in their contributions to the HWDI. Urban areas display fluctuations between 3% and 5% (Urban - 3% to 5%), suggesting changing heat wave durations in developed regions. Similarly, the Bare land cover class exhibits a consistent contribution of 15% to the HWDI (Bare - 15%), indicating a relatively stable heat wave duration in open land areas. The HWPT provides insights into the heat wave per time period experienced in different areas based on land cover characteristics. It can be observed that the Cropland class consistently experience about 11% of heat waves per time period from 2010 to 2022, indicating a relatively stable intensity of heat waves in agricultural areas. The Herbaceous, Shrubs, and Natural vegetation classes also maintain consistent percentage values of 12% to 14% (Herbaceous - 12% to 14%, Shrubs - 9% to 10%, Natural vegetation - 10% to 11%), suggesting a relatively uniform heat wave power in these land cover categories. However, the Tree cover class stands out in the HWPT table, displaying higher percentage values of 6% to 7% (HWPT: Tree cover - 6% to 7%). This suggests that areas with more extensive tree cover experience more intense heat waves compared to other land cover classes. Additionally, the Urban class shows fluctuations between 4% and 5% in its contribution to the HWPT (HWPT: Urban - 4% to 5%), indicating varying intensities of heat waves in urbanized regions.

The HWDI measures the length of heat waves in days and is an important indicator of how heat waves affect human health, agriculture, and ecosystems. HWPT, on the other hand, evaluates the heat wave across time. Positive regression coefficients for both HWDI and HWPT are found in the Am and AW climatic classes, demonstrating an increasing trend in heat wave duration and frequency with the independent variable. Ragatoa *et al*. reported similar observation in the coastal region (south) of Nigeria (Ragatoa *et al*., 2019).

The HWDI and HWPT regression coefficients for the Bsh and Bwh climatic classes are negative, indicating a decreasing trend in heat wave duration and frequency with the independent variable. On the contrary, Agada and Yakubu reported a positive temperature trend indicating a rise in the intensity of heat waves in the future for Yobe state, within the same region (Agada and Yakubu, 2022). In contrast, the HWDI and HWPT trends in the Af and Csh climatic classes differ. HWDI has a positive coefficient in the Af class, whereas HWPT has a significantly lower positive coefficient. HWDI has a positive coefficient in the Csh class, whereas HWPT has a greater positive coefficient. This implies that, while heat wave duration is increasing in both groups, heat wave frequency is increasing faster in the Csh class than in the Af class. The Bwh climatic class, which represents hot deserts, has the greatest HWDI and HWPT values of any climate class, indicating that exceptionally long and frequent heat waves are common. When compared to other climate classes, the tropical rainforest climate (Af) and tropical monsoon climate (Am) have lower HWDI and HWPT values, implying shorter and less frequent heat wave episodes. HWDI values vary in magnitude among climatic classes, with the highest values recorded in the Bsh and Bwh climate classes and relatively lower values observed in the Af, Am, Aw, and Csh classes. HWDI values vary across months within each climatic class, however the overall trend reveals that certain months have greater HWDI values than others. This agrees with Ragatoa *et al*., who reported the highest number of heat wave events and the highest number of days for heat wave duration and frequency in the Sahel climate region of Nigeria (Ragatoa *et al*., 2019). HWPT values also differ among climatic classes, with larger values observed in the Am and Aw classes vs the Af and Csh classes. Most months, the HWPT values in the Bsh and Bwh classes are relatively stable. There are swings in HWPT values among months, but the general trend shows that certain months have higher HWPT values than others. The months of January and April consistently have high HWDI and HWPT values across different climatic classes, indicating that extreme heat waves are typical during these months. November has high HWDI values in the Af, Am, and Csh climatic classes, as well as a high HWPT value in the Am class, indicating a common pattern of heat wave severity during the month. The HWDI values vary across climatic classes and seasons, although the general trend suggests that the winter months (DJF) have greater values than the other seasons. This pattern is seen in the classes Af, Am, Aw, Bsh, and Csh. In contrast, the Bwh class has greater HWDI values throughout the spring (MAM) season. The HWPT values vary among climatic classes and seasons as well. In all climate classifications, the DJF season consistently has greater HWPT values than other seasons. This shows that heat waves are more common in these areas during the winter months. The magnitude of HWPT values, however, differs across classes, with the Bsh and Bwh classes having larger HWPT values than the Af and Csh classes. When the HWDI and HWPT are compared, it is clear that certain land cover classes contribute consistently to both the HWDI and the HWPT, while others fluctuate. Notably, the contributions of the Urban and Bare classes to both indices vary, indicating different heat wave durations and intensities in developed and open land locations. To draw more definitive conclusions from these data, a more extensive analysis taking into account regional climatic trends, land cover characteristics, and additional contextual information would be required. According to these data, different climatic categories exhibit diverse patterns of heat wave properties. The HWDI values in the Bwh and Bsh climates are the greatest, indicating that heat waves endure longer, whereas the HWPT values in the Aw climate are the highest, showing that heat waves occur most frequently. This is in agreement with Agu, *et al*., who reported increase in the land surface temperature (LST) of Enugu over the years (Agu, *et al*., 2020). The HWDI and HWPT values in the Af climate are the lowest, indicating a less severe heat wave trend. It should be mentioned that the maximum and lowest numbers may vary depending on the month and climatic class. Heat waves are more common in hot, arid climates like Bwh and Bsh. Temperatures in these places can easily exceed 40°C (104°F) during the summer, and heat waves can last for many days or even weeks. High temperatures, little humidity, and intense sun rays can all combine to generate lethal heat stress conditions for humans and animals, as well as an increased risk of wildfires. Heat waves are also common in tropical regions such as Af, Am, and Aw, however they are not as severe as in Bwh and Bsh. Heat waves can be accompanied by high humidity levels in certain places, making the conditions much more uncomfortable and hazardous to human health. Furthermore, in tropical areas, the impacts of heat waves can be exacerbated by additional factors such as a lack of infrastructure, access to cooling systems, and limited healthcare resources. Heat waves, on the other hand, are less common in cooler regions such as Csh, where temperatures rarely exceed 30°C (86°F).

Conclusion: The study reveals variations in HWDI/HWPT values across climate categories, with positive regression coefficients for Af, Am, Aw, and Csh classes and negative coefficients for Bsh and Bwh classes. Higher values are observed in dry season months, reflecting seasonal heat wave variability. The study also examines land cover types' impact on heat wave characteristics, with barelands having the highest occurrence. This highlights the importance of considering KCCS when assessing heat waves and offers insights for targeted adaptation strategies.

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