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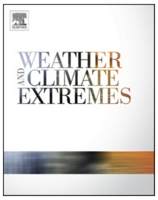

Heatwaves in Mozambique 1983–2016: Characteristics, trends and city-level summaries using high-resolution CHIRTS-daily

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ABSTRACT

The intensity, frequency, and duration of heatwaves are increasing worldwide. Still, heatwaves are systematically underreported and underresearched across the African continent. This study examines heatwaves across Mozambique, a country highly vulnerable to a variety of climate risks yet where heatwaves have received little to no attention. A spatio-temporal analysis was conducted for five heatwave characteristics (heatwave number, frequency, duration, amplitude, and magnitude) and corresponding trends from 1983 to 2016. This was done using the remotely sensed CHIRTS-daily, which presents one of the most accurate and highest resolution (5×5 km) daily temperature product currently available, especially for data-scarce regions. Three heatwave definitions were analyzed and compared, which are based on (1) the 90th percentile of daily maximum temperature (TX90), (2) the 90th percentile of daily minimum temperature (TN90), and (3) the Excess Heat Factor (EHF). Results were overlayed with high-resolution population data to obtain heatwave exposure and likely potential implications. Our findings show that Mozambique has experienced many heatwaves over the past decades. On average, 2–18.6 annual heatwave days (HWF) were recorded with the longest heatwaves (HWD) lasting X- 11.5 days. More and longer heatwaves were observed in the North and along the coast of Mozambique. Heatwave magnitude (HWM) ranged from 0.3 to 6.8 °C and amplitude (HWA) from 0.8 to 11.7 °C, with highest values in South and Central Mozambique. Heatwave events, days, and duration were found to be significantly increasing ($p < 0.05$) for many populated regions, yet trends for heatwave magnitude and amplitude were largely insignificant. A total of 13.6 million inhabitants (48% of the population) were found to be exposed to a significant increase in heatwave days, with most people exposed in Zambezia, followed by Nampula and Maputo province. City-level summaries of Maputo, Beira, Nampula, and Tete showed that these cities have been exposed to 50+ heatwave events since 1983. Overall, this study is one of the first to analyze historical heatwave events and trends on a high-resolution scale, both on country- and city-level scale, urgently required to increase awareness and spur action to reduce the current and future risk of extreme heat.

1. Introduction

Nearly every region around the world is experiencing an increase in the frequency, duration, and intensity of heatwaves (IPCC et al., 2021; Coughlan de Perez et al., 2018; Perkins et al., 2012). The past seven years have been the hottest on record by a clear margin (WMO, 2021), and with human activities continuing to increase greenhouse gas concentrations this trend will only continue to rise further. There is no single, universal definition for heatwaves, yet heatwaves are broadly described as a period of consecutive days where temperature, or temperature in combination with other weather variables, is unusually high and hazardous to human and natural systems (Singh et al., 2019; Perkins

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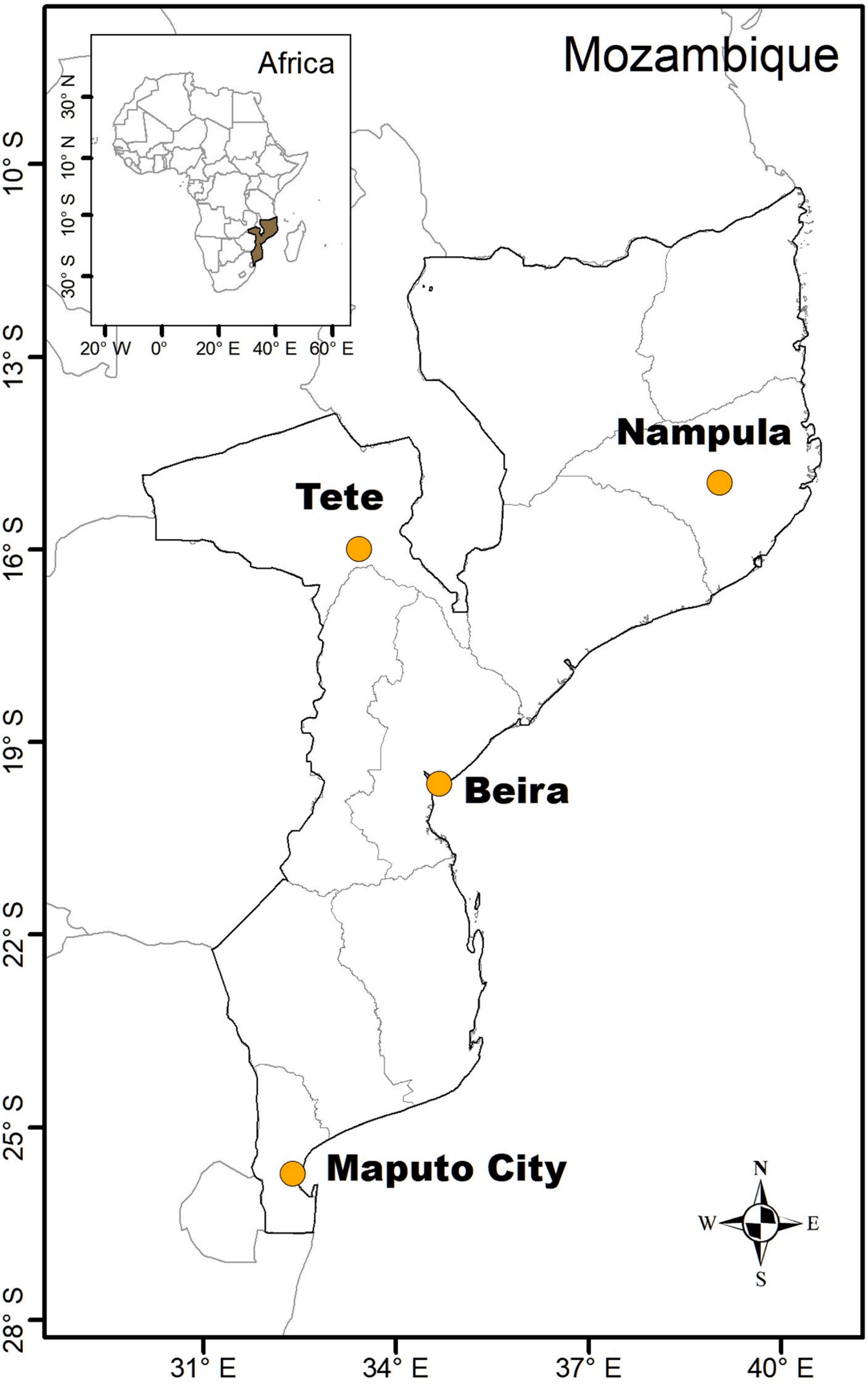

Fig. 1. Location of the study area: Mozambique and the four cities of Maputo, Beira, Tete, and Nampula.

and Alexander, 2013; McGregor et al., 2015). Heatwaves are known to negatively impact human health, cause economic damage through reduced productivity and lost work hours, and lead to agricultural losses (Singh et al., 2019; The World Bank, 2013; Li et al., 2015; McGregor et al., 2015; McElroy et al., 2022; International Labour Organization, 2019). Although anybody can suffer from heatwaves, heat-related impacts are highly unequal and disproportionately affect vulnerable groups of people such as elderly, children, (pregnant) women, outdoor workers, people living in informal settlements, migrants, and displaced individuals (Green et al., 2019; Singh et al., 2019).

Despite observations and model projections showing that nearly all regions around the world are increasingly confronted with more frequent and more intense heatwaves (IPCC et al., 2021), research has been predominantly focused on mid-latitude, temperate, and high-income countries. Heatwaves are consistently underreported and understudied across low-to middle-income countries, yet most visibly understudied across the African continent. Various studies have emphasized the urgent need to fill research gaps around heatwaves across African countries (Brimicombe et al., 2021; Campbell et al., 2018; van der Walt and Fitchett 2021; Russo et al., 2016; Mora et al., 2017).

As heatwaves have gone unreported across Africa, the extent and characteristics of heat-related impacts remain unknown (Harrington and

Otto, 2020). Between 1990 and 2019, the International Disaster Database (EM-DAT) recorded merely two heatwaves in Sub-Saharan Africa with limited to no impacts. In contrast, 83 heatwaves were reported across Europe, causing 140,000 deaths and over US$12 billions of damages (ibid.). This most likely also presents an underestimate, yet the gap between actual and recorded impacts is clearly bigger for Africa. The significant gaps in heatwave research across Africa are partially explained by the existing challenges with data collection, availability and quality, lack of local researchers, limited research funding, and publishing barriers when English is not the first language (Campbell et al., 2018; Kapwata, 2020; Ncongwane et al., 2021).

Over the past years, studies have increasingly provided evidence for significant increases in heatwave frequency, duration, and intensity across the African continent (Ceccherini et al., 2017; Marcotullio et al., 2021; Engdaw et al., 2021; Russo et al., 2016). Also various regional and national studies on heatwaves have been conducted, for example across the Sahel (Guigma et al., 2020; Oueslati et al., 2017; Ndiaye et al., 2022), North-Western Sahara (Vizy and Cook, 2012); the Middle East and North Africa region (Zittis et al., 2021); the southern African region (Meque et al., 2022); Kenya (Amou et al., 2021) and South Africa (van der Walt and Fitchett, 2021a, 2021b; Jagarnath et al., 2020; Wright et al., 2021). Meque et al. (2022) analyzed heatwaves characteristics across the southern African region, recording up to 3 heatwave events each year in some regions. Furthermore, El Niño Southern Oscillation (ENSO) was identified as one of the key climate drivers of heatwaves over this region (Meque et al., 2022). Still, there is a lack of country- and city-level scale research on heat extremes across Africa, including Mozambique. Mozambique is one of Africa's most vulnerable countries and is already highly exposed to many other climate risks such as sea-level rise and flooding, tropical cyclones, and severe droughts (Ministry of Foreign Affairs of the Netherlands, 2018; Bambaige et al., 2008). Still, heatwaves are not properly understood nor recognized as a risk across Mozambique. As a first step to increase knowledge and awareness of heatwaves in Mozambique, this study aimed to assess heatwave prevalence, characteristics, trends, and exposure over the past decades on a country-wide scale and by zooming into four populated cities (Maputo, Beira, Nampula, and Tete).

2. Materials and methods

2.1. Study area

Mozambique is located in southeastern Africa, bordering South Africa, Malawi, Eswatini, Zambia, and Zimbabwe. Situated at the intertropical zone, Mozambique contains a varied climate with a tropical to sub-tropical climate across the north and center, and semi-arid towards the south (USAID, 2017). The northwest of the country contains high plateaus and mountains which are often cooler compared to coastal lowlands. The climate of Mozambique is characterized by two main seasons. The hot and humid season lasts from October to March, with highest absolute temperatures observed along the coast and south of the country (Ministry of Foreign Affairs of the Netherlands, 2018). The cool and dry season lasts from May to September. This study provides a country-wide analysis and zooms into four cities (Maputo City, Beira, Nampula, and Tete) located across different geographic locations and climatic zones (Fig. 1).

2.2. Data

2.2.1. Temperature data (CHIRTS-daily)

The Climate Hazards Center InfraRed Temperature with Stations (CHIRTS)-daily is a newly developed, high-resolution (0.05° × 0.05°; approximately 5 × 5 km) dataset containing 2-m daily temperature on a quasi-global scale (60°S – 70°N) for the period of 1983–2016 (Funk et al., 2019). This dataset was developed by the Climate Hazards Center (CHC) and is openly available through: www.chc.ucsb.edu/data/chirtsdaily. CHIRTS-daily has been shown to match observational records of extreme temperatures more accurately compared to the robust global reanalysis ERA5 dataset, particularly across urban, data-scarce regions (Verdin et al., 2020; Tuholske et al., 2021). Therefore, this dataset represents the most accurate and highest resolution daily temperature product available, particularly useful across the African continent where there are geographically sparse and incomplete observational records (Verdin et al., 2020). Furthermore, CHIRTS-daily has already been used across a variety of recent studies across Africa (e.g., Amou et al., 2021; Reda et al., 2021; Leger et al., 2021; James et al., 2021; Parsons et al., 2022). For details on the development and validation of CHIRTS-daily see Verdin et al. (2020).

2.2.2. Population density (GRID3)

High-resolution population density (100 × 100 m) was obtained through the GRID3 dataset, developed by the WorldPop Research Group at the University of Southampton (openly available through: https://data.grid3.org/). This dataset was produced by disaggregating district-level population density (obtained from 2017 census data provided by the National Institute of Statistics; INE) into grid cells based on building footprint data. For further details on the development of the GRID3 dataset see Bondarenko et al. (2020).

2.3. Methodology

2.3.1. Heatwave definitions

There is no universal threshold or definition for what is considered a heatwave, and a variety of methods are used to quantify heatwaves across the literature. This makes it challenging to compare heatwave occurrences, characteristics, and impacts across regions. In efforts to move towards a more unified framework to quantify heatwaves, Perkins and Alexander (2013) proposed three heatwave definitions (TX90, TN90, and EHF) due to various advantages over other definitions. For example, due to their applicability across climates and regions, the quality of data required, and the feasibility of the method. These definitions have been adopted by WMO'S Expert Team on Sector-Specific Climate Indices (ET-SCI), together with the development of five heatwave characteristics and the open-source R Software package ClimPACT (Alexander and Herold, 2016). Altogether, these indices have resulted in significant contributions to the scientific understanding of temperature extremes on a global scale (Perkins et al., 2012; Perkins-Kirkpatrick and Lewis, 2020), across Australia (Perkins and Alexander, 2013), China (Shen et al., 2017), and various African regions (Abatan et al., 2016; van der Walt and Fitchett, 2021a; Gamal, 2019; Meque et al., 2022; Leger et al., 2021).

This study analyzes and compares the three heatwave definitions (TX90, TN90, and EHF) as proposed by (Perkins and Alexander, 2013) (with minor changes to the EHF-definition, as described in Perkins 2015). Calculations were done using the open-source package of ClimPACT2 (updated version of ClimPACT) and R Studio Software. All three definitions are based on relative thresholds, namely the 90th percentile of daily temperature values per grid cell for each calendar day, thus taking local conditions as well as seasonality into account.

(1) Definition 1: TX > TX90 for at least 3 consecutive days

(TX: maximum daily temperature, TX90: the 90th *percentile of TX*).

The 90th percentile for the maximum temperature was calculated using a chosen base period of 1983–2005. Furthermore, a 15-day running window centered on each calendar day was used to account for the seasonal cycle and increase the sample size. As a result, one unique threshold value for each day of the year and for each grid cell was obtained. A heatwave is measured when maximum temperature (TX) exceeds the 90th percentile of that calendar day (TX90), for a minimum of three consecutive days.

Table 1
Description of heatwave characteristics.

Characteristic	Description	Units
Heatwave number (HWN)	The number of heatwaves each year	Events
Heatwave frequency (HWF)	The number of heatwave days	Days
Heatwave duration (HWD)	Length of the longest yearly heatwave	Days
Heatwave magnitude (HWM)	Average temperature across all yearly heatwaves (EHF-definition: the average excess heat felt during all heatwaves)	°C (EHF-definition: °C^2)
Heatwave amplitude (HWA)	Highest temperature of the hottest yearly heatwave (EHF-definition: excess heat felt during the hottest temperature of the hottest yearly heatwave)	°C (EHF-definition: °C^2)

(2) Definition 2: TN > TN90 for at least 3 consecutive days

*(TN: minimum daily temperature, TN90: the 90*th *percentile of TN*).

The calculations as for definition (1) yet using minimum temperature.

(3) Definition 3: Excess Heat Factor (EHF) > 0

The Excess Heat Factor (EHF) is a combination of two excess heat indices, EHI(significance) (Eq. (1)) and EHI(acclimatization) (Eq. (2)). This definition considers the climatological significance of the extreme heat, as well as the acclimatization to heat that has occurred over the preceding 30 days (Alexander and Herold, 2016).

EHI(sig.) (Eq. (1)) describes the long-term temperature anomaly over a 3-day window against the 90th percentile threshold for the daily mean temperature, thus taking both minimum and maximum temperature into account. TM_i represents the mean temperature for day i and $TM90_i$ represents the climatological 90th percentile over the chosen base period (1983–2005), calculated for each calendar day i using a 15-day running window. EHI(sig.) must be positive for a heatwave to be recorded, meaning the average daily temperature is unusually high considering its local usual climate, for at least three consecutive days. EHI(accl.) (Eq. (2)) represents the anomaly over a 3-day window compared to the proceeding 30 days.

$$EHI(sig.) = [(TM_i + TM_{i-1} + TM_{i-2}) / 3] - TM90_i \qquad \text{Eq. 1}$$

$$EHI(accl.) = [(TM_i + TM_{i-1} + TM_{i-2}) / 3] - [(TM_{i-3} + \cdots + TM_{i-32}) / 3] \qquad \text{Eq. 2}$$

The EHF is a product of the above indices, and by multiplying it is ensured that the sign of EHF is the same as EHI(sig.). A heatwave is therefore calculated when EHF is positive, any additional positive value of EHI(accl.) adds to the EHF. The units of EHF are in °C^2. Overall, the EHF has a strong signal-to-noise ratio, meaning low-impact heatwaves are recorded as low-amplitude EHF events (Nairn and Fawcett, 2013).

$$EHF = \max[1, EHI(accl.)] x\ EHI(sig.) \qquad \text{Eq. 3}$$

2.3.2. Heatwave characteristics and climatologies

Five heatwave characteristics were calculated on an annual basis over the extended austral summer period of November to March from 1983/84 to 2015/16. The characteristics include heatwave number, frequency, duration, magnitude, and amplitude (Table 1). Next, the yearly values for each characteristic were averaged over the entire time period to obtain heatwave climatologies.

In addition, the two heatwave characteristics of heatwave magnitude (HWM) and amplitude (HWA) were modified, to obtain anomaly-based

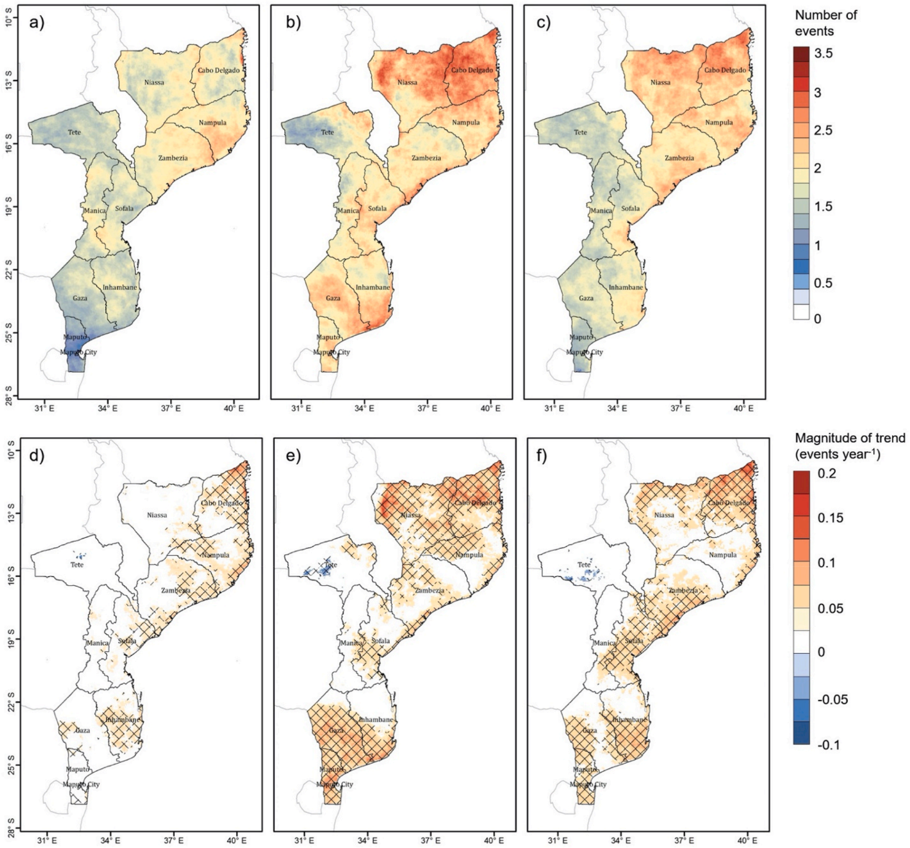

Fig. 2. Heatwave climatologies for heatwave number (HWN) using TX90 (a), TN90 (b), and EHF (c) heatwave definitions and corresponding trends (d–f). Trends are in events year^{-1}. Hatching indicates trends that are statistically significant at the 5% level.

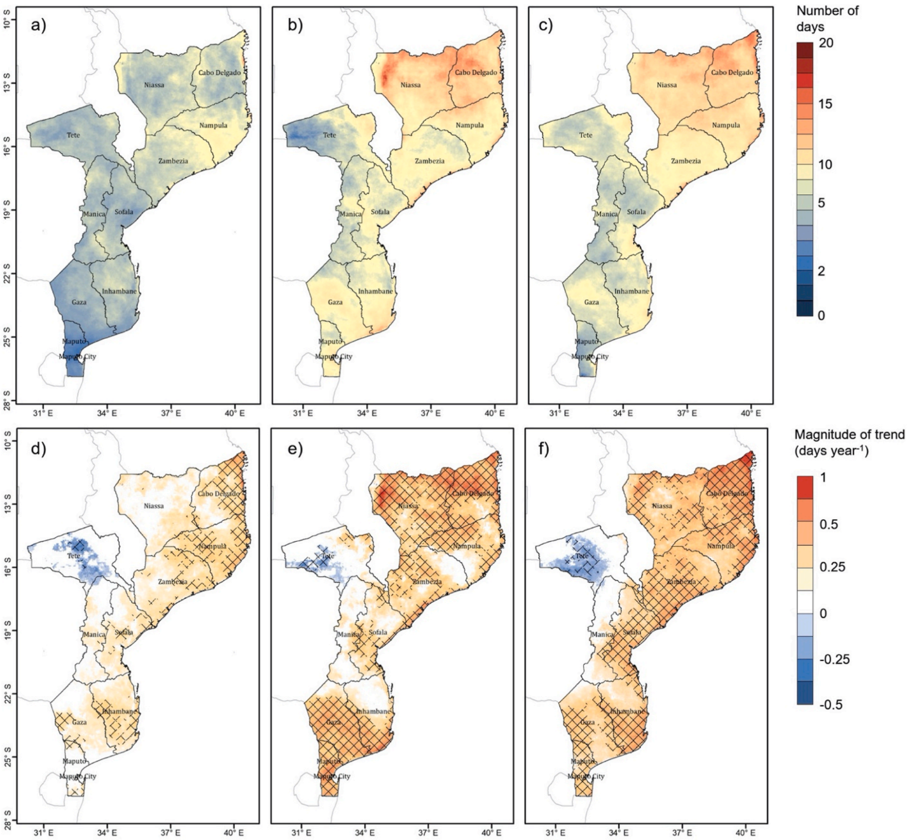

Fig. 3. As in Fig. 2, but for the number of heatwave days (HWF). Trends are in days year^{-1}. Hatching indicates trends that are statistically significant at the 5% level.

results and increase understanding of "how hot" heatwaves were compared to local summertime temperatures (as done in Perkins and Alexander (2013). Such results were thought to be a more useful indicator of heat-related impacts. HWM refers to the average temperature across all heatwaves in a given year, and HWA to the highest temperature of the hottest heatwave in a given year (Table 1). To calculate the anomalies, two steps were taken. First, the local, average summertime conditions were calculated for each grid cell by taking the average of maximum and minimum temperature values during the extended summer period (November–March) using a chosen base period of 1983–2005. Next, these average summertime temperature values were subtracted from the absolute HWM and HWA values. This calculation was only done for TX90-and TN90-definitions, as the EHF-definition is already anomaly-based.

2.3.3. *Trend analysis*

Annual trends for each heatwave characteristic were calculated using the non-parametric Mann Kendall (MK) test and Sen's slope estimator and computed at 5% significance level. The MK test is a non-parametric estimator which is commonly used for trend analysis of meteorological variables, as this test is robust against outliers and non-normally distributed data (Perkins and Alexander, 2013). Furthermore, this test has low sensitivity to inhomogeneous time series. Sen's slope estimator was used to quantify the magnitude of the trend (Sen, 1968). To compare trends of HWM and HWA across definitions, the square root of EHF was taken before analyzing the trends to obtain units of °C year^{-1}. All calculations were done using R Software.

2.3.4. *Population exposure (EHF-definition)*

Results from the trend analysis were overlayed with high-resolution population data to obtain the number of people exposed to a significant increase in heatwave days (HWF) and understand areas of likely potential implications from extreme heat. First, grid cells with significant increases in HWF ($p < 0.05$) were reclassified to 1 and the rest to 0. Next, population data (100 × 100 m) was aggregated to 5 × 5 km to match resolution with the heatwave data. Finally, these grid cells were multiplied by each other. This analysis was done using the EHF-definition, as this definition was thought to be most appealing from a climatological point of view (Perkins and Alexander, 2013) and provides a useful indicator of impacts on human health (Nairn et al., 2018). Calculations were done using ArcGIS Software (ArcMap 10).

2.3.5. *City-level summaries: Maputo City, Beira, Nampula, and Tete (EHF-definition)*

City-level summaries were obtained for four populated cities located in different geographical locations and climatic zones of Mozambique, namely Maputo City, Beira, Nampula, and Tete (Fig. 1). Calculations were done by averaging the grid cell values which overlapped with the administrative boundaries of each city, for each heatwave characteristic. Similar to the population exposure analysis (Section 2.3.4), the city-level summaries were calculated based on the EHF-definition, as this definition was thought to relate most to the impacts on human health (Nairn et al., 2018).

3. Results

3.1. *Heatwave climatologies & trends (1983–2016)*

3.1.1. *Number of heatwave events (HWN)*

The average number of heatwave events (HWN) from 1983 to 2016 is shown in Fig. 2a-c. On average, 1.7 (0.63–2.96) (minimum – maximum) heatwaves were measured using the TX90 definition, with fewest heatwaves in southern provinces (Fig. 2a). TN90 and EHF show similar results in terms of spatial variability and magnitude, measuring on

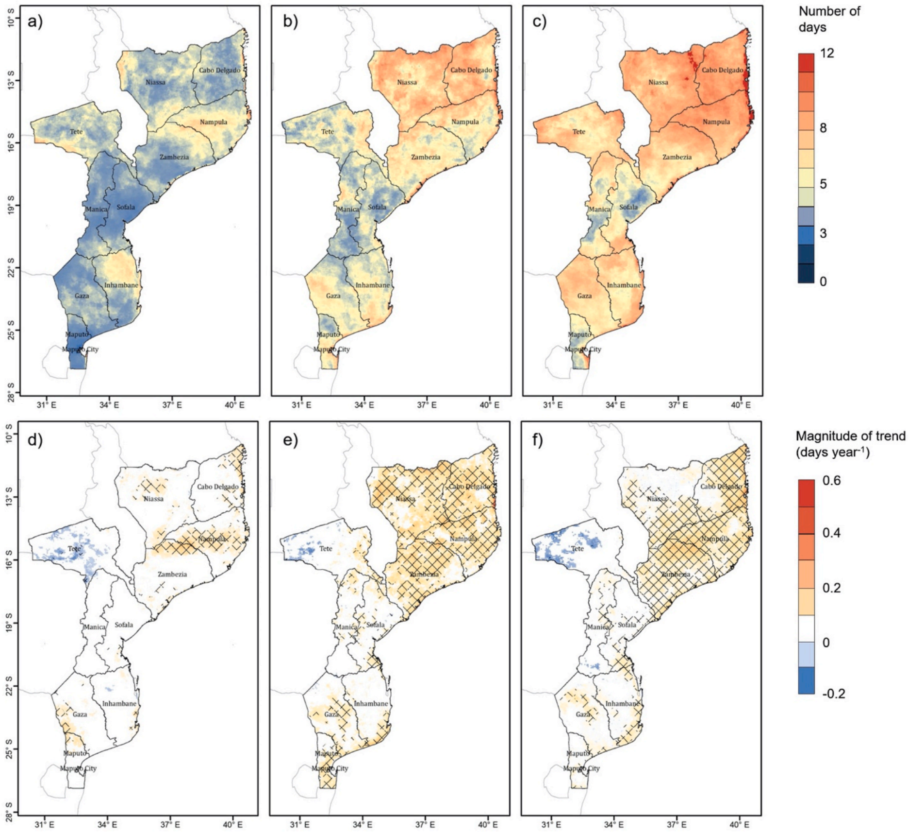

Fig. 4. As in Fig. 3, but for the duration of the longest yearly heatwave (HWD). Trends are in days/year. Hatching indicates trends that are statistically significant at the 5% level.

average 2.2 (1–3.2) and 1.95 (1.1–3) heatwaves per year (Fig. 2b and c). In other words, more night-time heatwaves (TN90) were recorded compared to day-time heatwaves (TX90).

The trend analysis revealed larger increases in the number of heatwave events based on TN90 compared to TX90, meaning the number of hot nights is increasing faster compared to hot days for most parts of Mozambique. TN90 and EHF show similar distributions of trends, with significantly positive trends of 0.10–0.17 heatwaves year^{-1} observed in the Southern provinces of Maputo and Gaza, Central provinces of Sofala and Zambezia, as well as Northern provinces of Niassa and Cabo Delgado (Fig. 2e and f). No significant trends were observed for Tete and parts of Manica and Nampula.

3.1.2. *Number of heatwave days (HWF)*

The average number of heatwave days (HWF) measured during the period of 1983–2016 is shown in Fig. 3a-c, showing similar spatial patterns as with HWN. Across definitions, TX90 measures fewest heatwaves with an average of 6.96 (2.12–16.94) heatwave days per year, with most heatwaves in Nampula province and least in Maputo province (Fig. 3a). TN90 and EHF climatologies are similar in spatial variability and magnitude, measuring on average 9.45 (4.15–16.61) and 9.44 (4.78–18.55) heatwave days per year respectively (Fig. 3b and c). For these definitions, most heatwave days were observed in the Northern provinces of Niassa and Cabo Delgado.

HWF were found to be significantly increasing by 0.5–1.03 days year^{-1} for a large part of Mozambique using the TN90 and EHF-definitions (Fig. 3e and f). The spatial coverage for statistically significant increasing trends for TN90 and EHF was found to be 44% and 39.8% of Mozambique respectively. This increase is visible in nearly all provinces except for Tete and Manica. To a lesser spatial extent and magnitude, but still visible, increasing trends were observed using the T×90-definition, with 0.2 days year^{-1} across the coastline and in parts of the provinces of Cabo Delgado, Nampula, Zambezia, Sofala, Inhambane, Gaza (in total covering 14.4% of Mozambique) (Fig. 3d). Across all definitions, a minor decreasing trend is observed in parts of Tete of −0.28 days per year.

3.1.3. *Duration of the longest yearly heatwave (HWD)*

The average duration of the longest yearly heatwave (HWD) during 1983–2016 is shown in Fig. 4a-c. The longest heatwaves are measured by EHF with an average of 5.87 (3.96–12.42) days across the country (Fig. 4c). This is followed by TN90 heatwaves, measuring 5.36 (3.97–10.4) days for the longest yearly heatwave on average (Fig. 4b). Both definitions contain longest heatwaves in the northeast of Mozambique, alongside the coast, and in the province of Gaza. For TX90, the average duration of the longest yearly heatwaves was found to be 4.65 (3.22–11.5) days (Fig. 4a).

For TX90 heatwaves, the duration of the longest heatwave events (HWD) is not changing significantly, with minor exceptions in the Northern provinces of Nampula and Zambezia (Fig. 4d) where a slight increase is observed. For TN90 and EHF, a significant increase of on average 0.3 days year^{-1} was found, mainly for northern Mozambique (Niassa, Cabo Delgado, Nampula and Zambezia), alongside the coast, and in Maputo province (Fig. 4e and f).

3.1.4. *Average temperature across all yearly heatwaves (HWM)*

Heatwave magnitude (HWM) was obtained by subtracting local summertime average temperature from the average temperature across all yearly heatwaves recorded (as described in Section 2.3.2). The local summertime temperatures were calculated from November to March using a base period of 1983–2005. Highest anomaly values were observed for Southern and Central provinces, in particular Gaza and Maputo province (Fig. 5a–c). Across definitions, TX90 recorded the highest anomalies of all definitions, with anomalies of on average

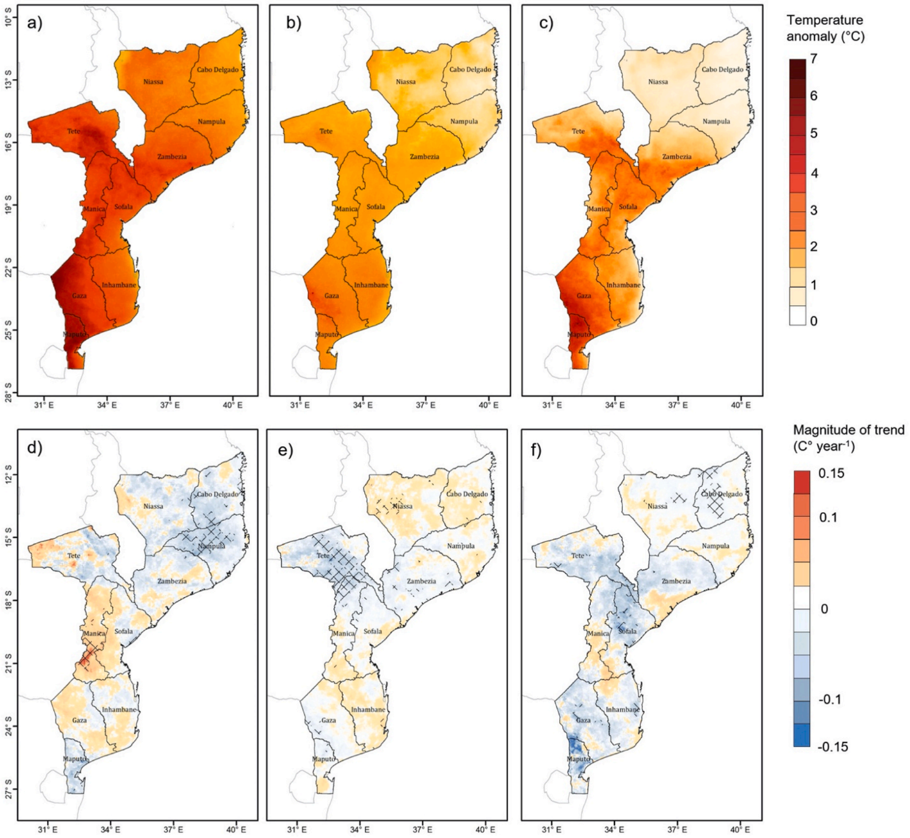

Fig. 5. As in Fig. 3, but for heatwave magnitude (HWM). The square root of the EHF has been taken before calculating the trends to compare trends between definitions. Trends are in °C year^{-1}. Hatching indicates trends that are statistically significant at the 5% level.

4.24 °C (1.48–6.77 °C). TN90 recorded anomalies of 2.25 °C (1.06–3.85 °C) and EHF 1.83 °C^2 (0.31–4.97 °C^2) above local summertime conditions.

Trends for heatwave magnitude were found to be largely not statistically significant across the country, except for parts of Manica (T×90) and minor parts of Niassa (EHF). Here, average heatwave conditions were found to be increasing with 0.12 °C year^{-1} and 0.05 °C year^{-1} respectively. Furthermore, decreasing trends were observed of −0.05 to −0.15 °C year^{-1} in parts of Nampula province (TX90), Tete (TN90), and Cabo Delgado (EHF) (Fig. 5d–f).

3.1.5. *Highest temperature of the hottest yearly heatwave (HWA)*

Heatwave amplitude (HWA) was obtained by subtracting local summertime average temperatures from the highest temperature of the hottest yearly heatwave (as described in Section 2.3.2). Local summertime average temperatures were calculated from November to March using a base period of 1983–2005. On average, TX90 contained the highest average anomalies of 5.89 °C (2.1–8.73) °C. For the EHF-definition, anomalies are on average 4.77 °C^2 (0.79–11.68 °C^2). TN90 contains the fewest variation of heatwave anomalies with on average 3.13 °C (1.61–5.4 °C) (Fig. 6e). Similar to the spatial patterns of heatwave magnitude, highest anomalies are observed for Southern Mozambique in Gaza and Maputo provinces, and lowest for northern Mozambique.

Trends for the highest temperature during the hottest yearly heatwave were found to be largely not statistically significant for most part of the country (Fig. 6d–f). Some significant increases were observed using the TX90 and TN90-defintion. TX90 showed increases of up to 0.2 °C year^{-1} for central provinces of Manica, Tete, and Sofala. TN90 showed increases of up to of 0.1 °C year^{-1} in northern provinces of Niassa, Cabo Delgado, Nampula as well as along the coast in Inhambane and southern Maputo (Fig. 6d and e).

3.2. *Population exposure (EHF-definition)*

To obtain the number of people exposed to increases in heatwaves and thus identify areas with likely potential implications, high-resolution population density data was overlayed with trends in heatwave days (based on the EHF-definition) (5 × 5 km). Overall, a total of 13.6 million inhabitants (48% of the population) were found to live in areas with a significant increase in heatwave days (p-value <0.05) (Table 2; Fig. 7). The provinces with highest percentage of people exposed include Maputo City and the rest of Maputo province and Inhambane, and provinces with lowest percentage of affected people include Tete and Manica.

3.3. *City-level summaries (EHF-definition)*

The heatwave characteristics for the cities of Maputo, Beira, Nampula and Tete were summarized using the EHF-definition (Table 3). The annual number of heatwave days (HWF) over time for each city are displayed in Fig. 8 and summaries of the other heatwave characteristics are in Supplementary Materials, Fig. S2. The year refers to the start of the heatwave season, thus values for 1983 refer to the summer season of 1983–1984.

From 1983 to 2016, all four cities experienced more than 50 heatwaves. 90th percentile values were found to be highest for Tete and lowest for Nampula, meaning Tete's heatwaves were calculated based on higher absolute temperatures. On average, each city experienced 1.6–2.2 heatwave events each year (HWN), with a high number of events in the summer of 1997/8 in Nampula (6.5 heatwaves), 2006/7 in Maputo City (8.5 heatwaves), and 2015/16 in all cities. Furthermore, the cities experienced an average of 7.6–10.6 heatwave days (HWF) per year. Exceptional long-lasting conditions of extreme heat were found in the summer of 2015/16. Beira, Nampula, and Tete experienced 28, 48,

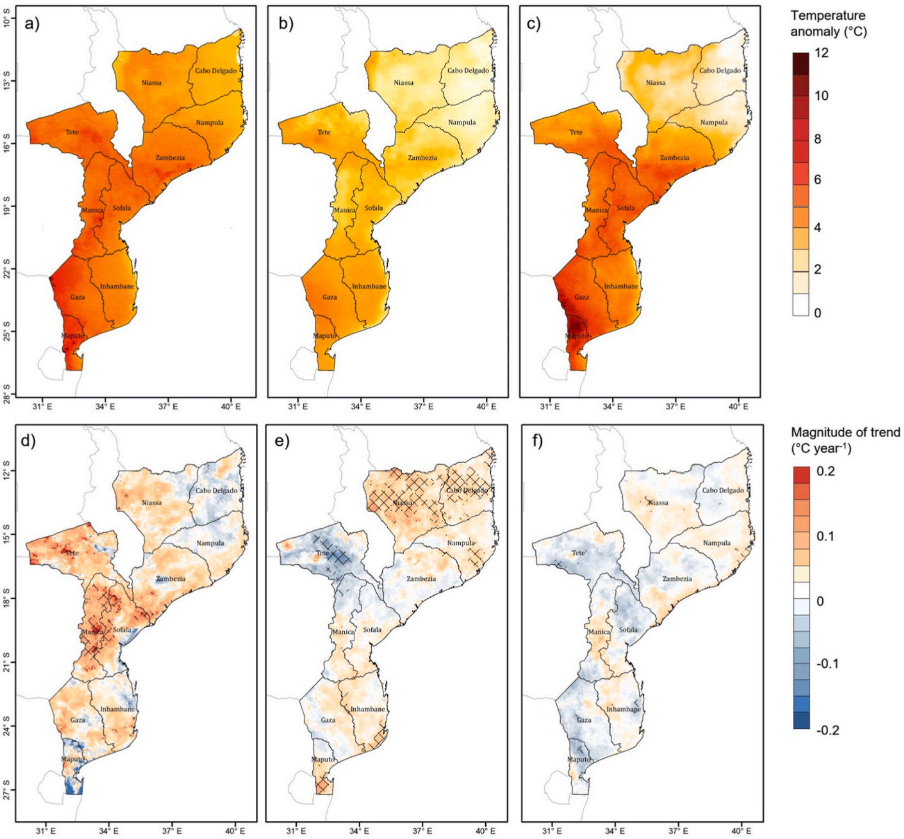

Fig. 6. As in Fig. 3, but for heatwave amplitude (HWA). The square root of the EHF has been taken before calculating the trends in order to compare trends between definitions. Trends are in °C year^{-1}. Hatching indicates trends that are statistically significant at the 5% level.

Table 2
Number and percentage of people exposed to a significant increase in heatwave days (HWF) per province.

Province	Total population (Census 2017)	Number of people exposed to increasing trends	Percentage of people exposed (%)
Tete	2,764,169	132,204	4.8
Manica	1,911,237	122,725	6.4
Gaza	1,446,654	240,003	16.6
Niassa	1,865,976	603,982	32.4
Nampula	5,483,382	2,340,779	42.7
Zambezia	5,110,787	3,017,267	59
Sofala	2,221,803	1,524,437	68.6
Cabo Delgado	2,333,279	1,607,772	68.9
Maputo[a]	2,507,098	1,824,207	72.8
Inhambane	1,496,824	1,190,054	79.5
Maputo City	1,101,170	959,361	87.1
Total	**28.242,379**	**13,562,791**	**48%**

[a] The numbers for Maputo are for Maputo province excluding Maputo City.

and 51 heatwave days respectively, whilst the average across the entire time-period was 8.6 heatwave days per year (Table 3). Maputo also contained a high number of heatwave days that year (31.5 days), but the maximum for Maputo was found in 2006/7 with 39 days. The duration of the longest yearly heatwave (HWD) across cities was on average 4.6–6.1 days per year. The longest heatwave was recorded during the summer of 2015/16 in Tete which lasted 16 consecutive days.

Highest average values for the excess heat felt across all heatwaves (HWM) and during the hottest heatwave day (HWA), were observed in Tete (7.2 °C^2 year^{-1}). The excess heat felt across all heatwaves (HWM) contains the highest anomalies in 1984/85 for Beira and Tete, in 1990 for Maputo City, and in 2013/14 for Nampula. In more recent years, average anomalies ranged between 1 and 3 °C^2. Anomalies on the hottest day of the hottest yearly heatwave (HWA) were found to be 21.6 and 5.8 °C^2 for Beira and Nampula in 1990, 14.7 °C^2 for Maputo in 2010, and 17.3 °C^2 for Tete in 2015.

4. Discussion and conclusion

This study is one of the first to examine heatwaves and trends on a high-resolution (5 × 5 km) scale across Mozambique, using the remotely sensed CHIRTS-daily temperature dataset to analyze three ET-SCI heatwave definitions for the period of 1983–2016. At present, CHIRTS-daily is thought to be the most accurate and highest resolution temperature dataset available. Our study therefore builds on the recent work by Meque et al. (2022), which uses ERA5 to calculate heatwaves and trends across the southern African region.

The definitions employed in this study allow for comparison of heatwave characteristics across countries and climates and are relevant to a variety of important sectors. All definitions are equally “correct”, yet one may be more chosen over another dependent on the purpose of the end user. For example, outdoor workers, engineering, and transport sectors might be more interested in TX90-based heatwaves, the agricultural sector in TN90-based heatwaves, and the health sector in EHF-based heatwaves (Nairn et al., 2018).

No heatwave definition or thresholds employed by Mozambique National Institute of Meteorology (INAM) was found publicly available. Since weather stations across Mozambique are sparsely located and span across relatively short time-periods, establishing appropriate thresholds for early warning systems can be challenging. Our results provide insight into what appropriate thresholds might look like across the country,

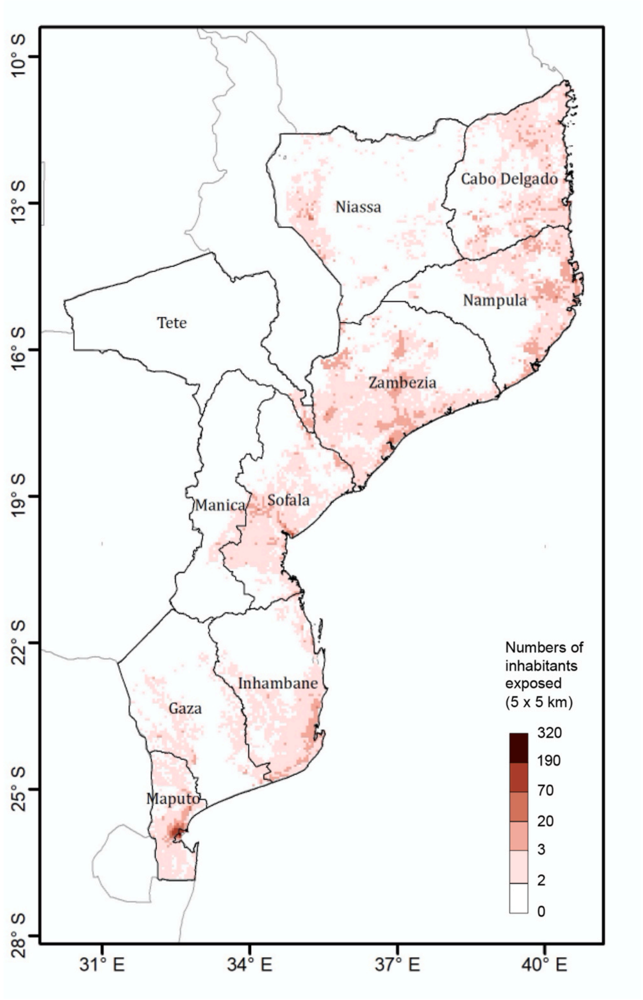

Fig. 7. Number of people exposed to a significant increase (p-value < 0.05) in heatwave days (HWF) across Mozambique using the EHF-definition. Grid cells with increasing trends in heatwave days (p-value <0.05) were overlayed with population density (5 × 5 km) (Data source GRID3: https://grid3.org/). Results show most people to be exposed in the province of Zambezia, followed by Nampula and Maputo province.

based on local 90th percentile values. These values were found to be highly variable across the country, with differences up to 15 °C (Supplementary Materials, Fig. S1, Table S1). This depicts the complexity in employing one temperature threshold for the whole country in an early warning system. In addition, in order to develop an operational and relevant early warning system, thresholds should be validated with local impact data (Nissan et al., 2017) and may include expert judgement and experience (McGregor et al., 2015). Heat-related impacts may already be observed at lower temperature thresholds than at the 90th percentile. This may be the case in tropical regions due to high humidity levels, or in vulnerable regions where people and systems have low capacity to cope with extreme heat (Gasparrini et al., 2015; Pasquini et al., 2020; Strathearn et al., 2022). However, CHIRTS-daily is currently only available until 2016 and therefore not usable in the context for monitoring or early warnings of heatwaves.

In contrast to the EM-DAT where no heatwaves were previously recorded for Mozambique, this study reveals many heatwave events over the period of 1983–2016, with varying characteristics across space. On average, the number for heatwave events (HWN), days (HWF), and duration of the longest yearly heatwave (HWD) were higher for Northern Mozambique and along the coast, whereas higher heatwave magnitude (HWM) and amplitude (HWA) were found for the Southern Mozambique. These spatial patterns are consistent with Meque et al. (2022) and may be explained by the different climates across the country. Northern Mozambique contains a tropical climate and experiences less seasonal and diurnal variation in temperature compared to the semi-arid South. Therefore, 90th percentile thresholds are lower in the tropical north, and are more easily exceeded, leading to a higher number of heatwaves. Although lower heatwave intensities are observed for the tropical north, in reality, "apparent" temperatures might be higher due to high levels of humidity.

Our trend analysis revealed significant increases in heatwave events (HWN), heatwave days (HWF), and duration of the longest heatwave (HWD) across a large part of Mozambique. This upward trend is consistent across definition, yet stronger for TN90 and EHF-heatwaves. This is consistent with global studies which show night-time warming is increasing faster compared to day-time warming (Cox et al., 2020; Sun et al., 2019), which is especially threatening to human health. This is in line with Meque et al. (2022), yet they find increasing trends on a much smaller spatial extent, exclusively for northern parts Mozambique. This could be explained by the different datasets and corresponding time range used (ERA5: 1981–2017 versus CHIRTS-daily: 1983–2016). Trends for heatwave magnitude (HWM) and amplitude (HWA) were found to be largely insignificant over the time-period analyzed, except for minor parts across Manica, Cabo Delgado and Niassa. The fact that HWM is decreasing in some areas may be explained by the fact that heatwaves are getting longer, thus dampening any increase in average temperature conditions (Perkins and Alexander 2013). Therefore, the *cumulative* magnitude may be a better indicator to capture heatwave intensity which should be considered in future studies (Perkins-Kirkpatrick and Lewis, 2020). As HWA is based on a single day, it is not affected by any changes in heatwave duration. Still, for the regions where trends are significant, trends for heatwave amplitude (HWA) are nearly twice as large compared to heatwave magnitude (HWM), meaning the intensity of heatwaves there is increasing faster compared to the average heatwave conditions. This indicates that the most extreme part of a heatwave is increasing, especially for parts of Central and North Mozambique.

Table 3

Summary of heatwave characteristics for Maputo, Beira, Nampula, and Tete for 1983–2016.

City	90th percentile (°C)[a]		Number of heatwave events (HWN)	Number of heatwave days (HWF)	Duration of longest heatwave event (HWD)	Average excess heat felt across all yearly heatwaves (HWM)	Excess heat felt during hottest day of hottest heatwave (HWA)
	TX90	*TN90*	*Average (events) (min-max)*	*Average (days year^{-1}) (min-max)*	*Average (days) (min-max)*	*Average (°C^2 year^{-1}) (min-max)*	*Average (°C^2 year^{-1}) (min-max)*
Maputo	35	27.5	1.6 (0–**8.5**)	7.7 (0–39.2)	5.4 (3–10.6)	2.3 (0.15–5.7)	6.3 (0.3–14.7)
Beira	35.7	26.9	2.1 (0–5.8)	8.6 (0–28)	4.6 (3–10.3)	2.2 (0.4–5)	6.4 (0.9–**21.6**)
Nampula	34.4	24.7	**2.2** (0–6.5)	**10.6** (0–47.8)	**6.1** (3–14)	0.7 (0.06–1.7)	1.9 (0.1–5.8)
Tete	**39.4**[b]	**28.8**	1.6 (0–5.3)	7.6 (0–**50.9**)	5.2 (3–**16**)	**3** (0.8–**8.7**)	**7.2** (2.1–17.3)

[a] The 90th percentile was calculated over the extended austral summer period (November–March) by taking the average of the calculated 90th percentile over each calendar day.

[b] Numbers in **bold** indicate the highest value across the cities.

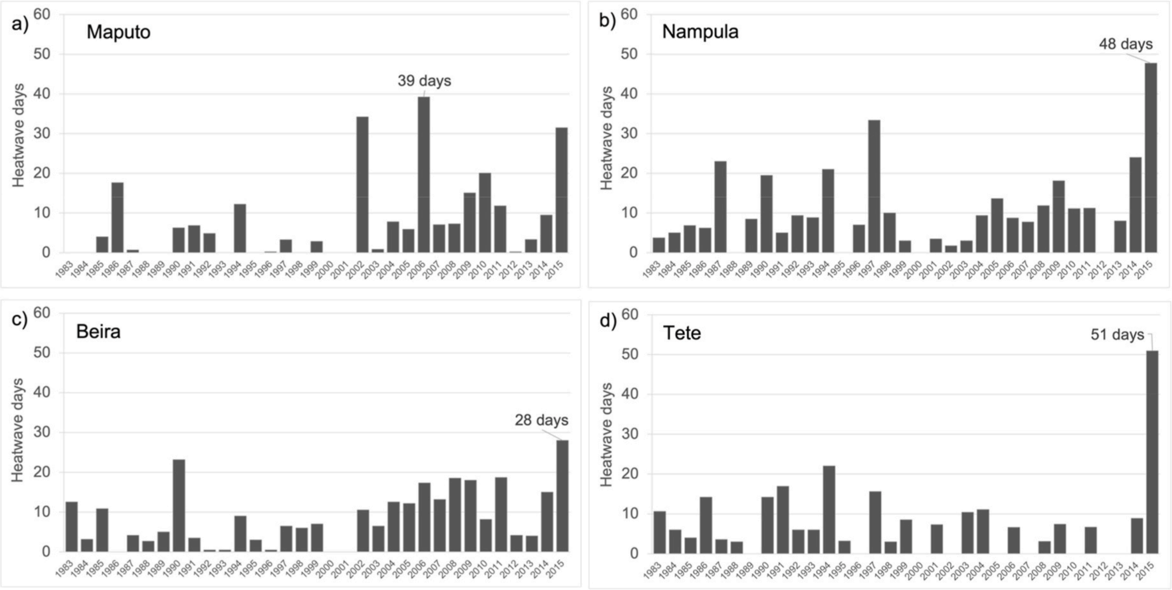

Fig. 8. Number of heatwave days for Maputo (a), Nampula (b), Beira (c), and Tete (d) across 1983–2016. Numbers for 1983 refer to the extended summer season (November–March) of 1983–1984. Maximum values across the time period are labeled for each city.

During 1983 to 2016, the four populated cities of Maputo, Beira, Nampula, and Tete experienced over 50 heatwaves each. One of the most long-lasting conditions of extreme heat were observed during the summer of 2015/16, with exceptional conditions of 28 days (Beira) up to 51 days (Tete) of extreme heat, which coincided with a strong El Niño event. These unprecedented conditions were observed over many other parts of Africa (Engdaw et al., 2021; Russo et al., 2016; Amou et al., 2021; Brimicombe et al., 2021; Kapwata 2020). Recently, Meque et al. (2022) identified ENSO as one of the key climatic drivers of heatwaves across the southern African region, which thus might (partially) explain the long-lasting heatwave conditions of 2015/16.

The recorded heatwaves in this study have likely resulted in a variety of impacts, yet currently there is no understanding of the magnitude or characteristics of these impacts. Heatwaves can result in negative impacts on human health, decrease productivity of outdoor workers, and cause losses of agricultural crops and livestock (McGregor et al., 2015). A large part of Mozambique's population is already particularly vulnerable due to various existing socio-economic challenges, and therefore contain limited ability to cope with heat extremes. Our results indicate that a large number of Mozambique's population already live in areas where significant increases in heatwave days were measured. With existing societal trends such as population growth and urbanization, exposure to extreme heat is only expected to increase further (Tuholske et al., 2021). The fact that currently there is extremely limited to no understanding of heatwaves and local impacts across Mozambique and other African countries is highly worrying, especially considering the rate at which global temperatures are increasing.

We also acknowledge this study has limitations. First, despite the advantages related to the heatwave definitions employed, humidity is not included in those. Humidity may play an important role in amplifying health impacts even at lower temperature thresholds than what would be considered climatologically extreme (Gasparrini et al., 2015; Pasquini et al., 2020; Strathearn et al., 2022). This is mainly of importance for the tropical regions of Mozambique, mostly in the north of the country. Next to the five heatwave characteristics calculated in this study, additional metrics could provide relevant insights, including first heatwave timing (HWT), heatwave season duration (HWS), and cumulative heatwave magnitude (HWC) (Perkins-Kirkpatrick and Lewis, 2020; Reddy et al., 2021). Furthermore, heatwaves were calculated over the extended summer period. Yet, heatwaves might take place in other months as well, particularly across tropical regions which experience higher temperature conditions year-round. It would therefore be useful to extend the heatwave calculations over the full year. On the other hand, the most intense and therefore impactful heatwaves are thought to take place in the summer period.

Many research gaps remain to be filled around heatwaves and risks across Mozambique. We urgently need to increase our understanding of heat-related impacts and the specific demographics of the people affected by extreme heat. In cases where there is inadequate quantitative data, qualitative research can provide useful information around heat-related impacts. Furthermore, the role of humidity and humid heatwaves across Mozambique should be investigated (e.g., through combined indices such as the Heat Index or Wet Globe Bulb Temperature). Lastly, while the evidence base around heatwaves and heat-health risks across Africa is growing, researchers and practitioners should simultaneously focus on researching feasible and local adaptation solutions that prove successful in reducing heat risk of the most vulnerable.

In conclusion, from 1983 to 2016, Mozambique has experienced many heatwaves and the number of heatwave events, days, and duration of the longest heatwave is significantly increasing across a large part of the country. The populated cities of Maputo, Beira, Nampula, and Tete have been exposed to 50+ heatwave events with exceptional long-lasting heatwave conditions during the summer of 2015/16. These events have likely impacted livelihoods, yet at present there is no understanding of the magnitude and characteristics of heat-related impacts. Overall, this study increases understanding of heatwave occurrence and variability across Mozambique on a high-resolution scale. These results provide the step forward towards understanding and recognizing heatwaves as a serious climate risk across Mozambique. The methodology used in this study is widely applicable and can be transferred to other data-scarce countries across Africa that are in high need of research on heat extremes.

Author contributions

Conceptualization and design of the study, CPM, MK, JB. Data analysis and interpretation, CPM, IP, KG. Visualization, CPM. Writing, reviewing, and editing, all authors. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wace.2023.100565.

References

Abatan, A.A., Abiodun, B.J., Lawalc, K.A., Gutowski, W.J., 2016. Trends in extreme temperature over Nigeria from percentile-based threshold indices. Int. J. Climatol. 36, 2527–2540. https://doi.org/10.1002/joc.4510.

Alexander, L., Herold, N., 2016. ClimPACT2. Indices and software. A document prepared on behalf of the commission for climatology (CCl) expert Team on sector-specific climate. Indice 46.

Amou, M., Gyilbag, A., Demelash, T., Xu, Y., 2021. Heatwaves in Kenya 1987–2016: facts from CHIRTS high resolution satellite remotely sensed and station blended temperature dataset. Atmosphere 12. https://doi.org/10.3390/atmos12010037.

Bambaige, A.J., Cuamba, B., dos Anjos Hauengue, M., 2008. CC and Health in Mozambique (Clacc).

Bondarenko, M., Jones, P., Leasure, D., Lazar, A., Tetem, A., 2020. Census Disaggregated Gridded Population Estimates for Mozambique (2017). version 1.1. WorldPop, Univ. Southampt., pp. 1–14. https://doi.org/10.5258/SOTON/WP00672

Brimicombe, C., Napoli, C. Di, Cornforth, R., Pappenberger, F., 2021. Characteristics of Heatwaves in Africa : Morocco 2000 and South Africa 2015/16, pp. 1–22.

Campbell, S., Remenyi, T.A., White, C.J., Johnston, F.H., 2018. Heatwave and health impact research: a global review. Health Place 53, 210–218. https://doi.org/10.1016/j.healthplace.2018.08.017.

Ceccherini, G., Russo, S., Ameztoy, I., Francesco Marchese, A., Carmona-Moreno, C., 2017. Heat waves in Africa 1981-2015, observations and reanalysis. Nat. Hazards Earth Syst. Sci. 17, 115–125. https://doi.org/10.5194/nhess-17-115-2017.

Coughlan de Perez, E., Van Aalst, M., Bischiniotis, K., Mason, S., Nissan, H., et al., 2018. Global predictability of temperature extremes. Environ. Res. Lett. 13 https://doi.org/10.1088/1748-9326/aab94a.

Cox, D.T.C., Maclean, I.M.D., Gardner, A.S., Gaston, K.J., 2020. Global variation in diurnal asymmetry in temperature, cloud cover, specific humidity and precipitation and its association with leaf area index. Global Change Biol. 26, 7099–7111. https://doi.org/10.1111/gcb.15336.

Engdaw, M.M., Ballinger, A.P., Hegerl, G.C., Steiner, A.K., 2021. Changes in temperature and heat waves over Africa using observational and reanalysis data sets. Int. J. Climatol. 42, 1165–1180. https://doi.org/10.1002/joc.7295.

Funk, C., Peterson, P., Peterson, S., Shukla, S., Davenport, F., et al., 2019. A high-resolution 1983–2016 TMAX climate data record based on infrared temperatures and stations by the climate hazard center. J. Clim. 32, 5639–5658. https://doi.org/10.1175/JCLI-D-18-0698.1.

Gamal, G., 2019. Historical and future extreme temperature indices of greater cairo region, Egypt. Bull. la Société Géographie d'Egypte 92, 40–52. https://doi.org/10.21608/bsge.2019.90372.

Gasparrini, A., Guo, Y., Hashizume, M., 2015. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. Environnement, Risques & Santé 14, 464–465. https://doi.org/10.1016/S0140-6736(14)62114-0.

Green, H., Bailey, J., Schwarz, L., Vanos, J., Ebi, K., et al., 2019. Impact of heat on mortality and morbidity in low and middle income countries: a review of the epidemiological evidence and considerations for future research. Environ. Res. 171, 80–91. https://doi.org/10.1016/j.envres.2019.01.010.

Guigma, K.H., Todd, M., Wang, Y., 2020. Characteristics and thermodynamics of Sahelian heatwaves analysed using various thermal indices. Clim. Dynam. 55, 3151–3175. https://doi.org/10.1007/s00382-020-05438-5.

Harrington, L.J., Otto, F.E.L., 2020. Reconciling theory with the reality of African heatwaves. Nat. Clim. Change 10, 794–795. https://doi.org/10.1038/s41558-020-0888-8.

International Labour Organization, 2019. Working on a Warmer Planet: the Impact of Heat Stress on Labor Productivity and Decent Work.

IPCC: Climate Change 2021, 2021. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y. (Eds.), The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 3949. Cambridge Univ. Press.

Jagarnath, M., Thambiran, T., Gebreslasie, M., 2020. Heat stress risk and vulnerability under climate change in Durban metropolitan, South Africa—identifying urban planning priorities for adaptation. Clim. Change 163, 807–829. https://doi.org/10.1007/s10584-020-02908-x.

James, K., Daniel, O., George, O., Gilbert, O., Joshua, O., 2021. Long-term spatial-temporal temperature characteristics of a pastoral ecosystem in Kajiado County, Kenya. Afr. J. Agric. Res. 17, 896–906. https://doi.org/10.5897/ajar2021.15544.

Kapwata, T., 2020. Heat Extremes and Impacts on Mortality in South Africa : towards the Development of a Heat Health Early Warning System by Thandi Kapwata Submitted in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy (Geography) in the Facult.

Leger, M., Quenum, D., Nkrumah, F., Ama, N., Klutse, B., et al., 2021. Spatiotemporal Changes in Temperature and Precipitation in West Africa . Part I : Analysis with the CMIP6 Historical Dataset.

Li, M., Gu, S., Bi, P., Yang, J., Liu, Q., 2015. Heat waves and morbidity: current knowledge and further direction-a comprehensive literature review. Int. J. Environ. Res. Publ. Health 12, 5256–5283. https://doi.org/10.3390/ijerph120505256.

Marcotullio, P.J., Keßler, C., Fekete, B.M., 2021. The future urban heat-wave challenge in Africa: exploratory analysis. Global Environ. Change 66. https://doi.org/10.1016/j.gloenvcha.2020.102190.

McElroy, S., Ilango, S., Dimitrova, A., Gershunov, A., Benmarhnia, T., 2022. Extreme heat, preterm birth, and stillbirth: a global analysis across 14 lower-middle income countries. Environ. Int. 158, 106902 https://doi.org/10.1016/j.envint.2021.106902.

McGregor, G.R., Bessemoulin, P., Ebi, K., Menne, B., 2015. Heatwaves and Health: Guidance on Warning-System Development, 114.

Meque, A., Pinto, I., Maúre, G., Beleza, A., 2022. Understanding the Variability of Heatwave Characteristics in Southern Africa. Weather Clim. Extrem., 100498 https://doi.org/10.1016/j.wace.2022.100498

Ministry of Foreign Affairs of the Netherlands, 2018. Climate Change Profile Mozambique, 20. Minist. Foreign Aff. Netherlands.

Mora, C., Dousset, B., Caldwell, I.R., Powell, F.E., Geronimo, R.C., et al., 2017. Global risk of deadly heat. Nat. Clim. Change 7, 501–506. https://doi.org/10.1038/nclimate3322.

Nairn, J., Fawcett, R., 2013. Defining Heatwaves: Heatwave Defined as a Heat-Impact Event Servicing All Communiy and Business Sectors in Australia, p. 84.

Nairn, J., Ostendorf, B., Bi, P., 2018. Performance of excess heat factor severity as a global heatwave health impact index. Int. J. Environ. Res. Publ. Health 15. https://doi.org/10.3390/ijerph15112494.

Ncongwane, K.P., Botai, J.O., Sivakumar, V., Botai, C.M., 2021. A literature review of the impacts of heat stress on human health across africa. Sustain. Times 13, 1–27. https://doi.org/10.3390/su13095312.

Ndiaye, O., Khemesse, M., Ndiaye, N., Ndiaye, P.N., Diene, N., 2022. Toward experimental heat-health early warning in africa. Bull. Am. Meteorol. Soc. 1–47 https://doi.org/10.1175/bams-d-20-0140.1.

Nissan, H., Burkart, K., Coughlan de Perez, E., Van Aalst, M., Mason, S., 2017. Defining and predicting heat waves in Bangladesh. J. Appl. Meteorol. Climatol. 56, 2653–2670. https://doi.org/10.1175/JAMC-D-17-0035.1.

Oueslati, B., Pohl, B., Moron, V., Rome, S., Janicot, S., 2017. Characterization of heat waves in the Sahel and associated physical mechanisms. J. Clim. 30, 3095–3115. https://doi.org/10.1175/JCLI-D-16-0432.1.

Parsons, D., Stern, D., Ndanguza, D., Sylla, M.B., 2022. Evaluation of satellite-based air temperature estimates at eight diverse sites in africa. Climate 10, 98. https://doi.org/10.3390/cli10070098.

Pasquini, L., van Aardenne, L., Godsmark, C.N., Lee, J., Jack, C., 2020. Emerging climate change-related public health challenges in Africa: a case study of the heat-health vulnerability of informal settlement residents in Dar es Salaam, Tanzania. Sci. Total Environ. 747, 141355 https://doi.org/10.1016/j.scitotenv.2020.141355.

Perkins, S.E., 2015. A review on the scientific understanding of heatwaves-Their measurement, driving mechanisms, and changes at the global scale. Atmos. Res. 164–165, 242–267. https://doi.org/10.1016/j.atmosres.2015.05.014.

Perkins, S.E., Alexander, L.V., 2013. On the measurement of heat waves. J. Clim. 26, 4500–4517. https://doi.org/10.1175/JCLI-D-12-00383.1.

Perkins, S.E., Alexander, L.V., Nairn, J.R., 2012. Increasing frequency, intensity and duration of observed global heatwaves and warm spells. Geophys. Res. Lett. 39, 1–5. https://doi.org/10.1029/2012GL053361.

Perkins-Kirkpatrick, S.E., Lewis, S.C., 2020. Increasing trends in regional heatwaves. Nat. Commun. 11, 1–8. https://doi.org/10.1038/s41467-020-16970-7.

Reda, K.W., Liu, X., Tang, Q., Gebremicael, T.G., 2021. Evaluation of global gridded precipitation and temperature datasets against gauged observations over the upper tekeze river basin, Ethiopia. J. Meteorol. Res. 35, 673–689. https://doi.org/10.1007/s13351-021-0199-7.

Reddy, P.J., Perkins-Kirkpatrick, S.E., Sharples, J.J., 2021. Intensifying Australian heatwave trends and their sensitivity to observational data. Earth's Future 9, e2020EF001924. https://doi.org/10.1029/2020EF001924.

Russo, S., Marchese, A.F., Sillmann, J., Immé, G., 2016. When will unusual heat waves become normal in a warming Africa? Environ. Res. Lett. 11 https://doi.org/10.1088/1748-9326/11/5/054016.

Sen, P.K., 1968. Estimates of the regression coefficient based on kendall's tau. J. Am. Stat. Assoc. 63, 1379–1389. https://doi.org/10.1080/01621459.1968.10480934.

Shen, X., Liu, B., Lu, X., Fan, G., 2017. Spatial and temporal changes in daily temperature extremes in China during 1960–2011, Theor. Appl. Climatol. 130, 933–943. https://doi.org/10.1007/s00704-016-1934-3.

Singh, R., Arrighi, J., Jjemba, E., Strachan, K., Spires, M., et al., 2019. Heatwave Guide for Cities. Red Cross Red Crescent Clim. Cent. https://doi.org/10.1088/1751-8113/44/8/085201.

Strathearn, M., Osborne, N.J., Selvey, L.A., 2022. Impact of low-intensity heat events on mortality and morbidity in regions with hot, humid summers: a scoping literature review. Int. J. Biometeorol. 1013–1029. https://doi.org/10.1007/s00484-022-02243-z.

Sun, X., Ren, G., You, Q., Ren, Y., Xu, W., et al., 2019. Global diurnal temperature range (DTR) changes since 1901. Clim. Dynam. 52, 3343–3356. https://doi.org/10.1007/s00382-018-4329-6.

The World Bank, 2013. Turn down the heat: climate extremes, regional impacts, and the case for resilience. A Report of the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics 346–347.

Tuholske, C., Caylor, K., Funk, C., Verdin, A., Sweeney, S., et al., 2021. Global urban population exposure to extreme heat. Proc. Natl. Acad. Sci. U. S. A 118, 1–9. https://doi.org/10.1073/pnas.2024792118.

USAID, 2017. Climate risk profile: Mozambique. USAID Clim. Chang. Integr. Support 1–5.

Verdin, A., Funk, C., Peterson, P., Landsfeld, M., Tuholske, C., et al., 2020. Development and validation of the CHIRTS-daily quasi-global high-resolution daily temperature data set. Sci. Data 7, 1–14. https://doi.org/10.1038/s41597-020-00643-7.

Vizy, E.K., Cook, K.H., 2012. Mid-twenty-first-century changes in extreme events over northern and tropical Africa. J. Clim. 25, 5748–5767. https://doi.org/10.1175/JCLI-D-11-00693.1.

van der Walt, A.J., Fitchett, J.M., 2021a. Exploring extreme warm temperature trends in South Africa: 1960–2016. Theor. Appl. Climatol. 143, 1341–1360. https://doi.org/10.1007/s00704-020-03479-8.

van der Walt, A.J., Fitchett, J.M., 2021b. Extreme temperature events (ETEs) in South Africa: a review. S. Afr. Geogr. J. 00, 1–20. https://doi.org/10.1080/03736245.2021.1907219.

WMO, 2021. Global annual to decadal climate update. Wmo 1–16.

Wright, C.Y., Kapwata, T., du Preez, D.J., Wernecke, B., Garland, R.M., et al., 2021. Major climate change-induced risks to human health in South Africa. Environ. Res. 196, 110973 https://doi.org/10.1016/j.envres.2021.110973.

Zittis, G., Hadjinicolaou, P., Almazroui, M., Bucchignani, E., Driouech, F., et al., 2021. Business-as-usual will lead to super and ultra-extreme heatwaves in the Middle East and North Africa, npj Clim. Atmos. Sci. 4 https://doi.org/10.1038/s41612-021-00178-7.