Heat Wave Characteristics in the Context of Climate Change over the Past 50 Years in Botswana

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Abstract

Heat waves have impacts on human health, society and the economy. This study seeks to improve the understanding of their characteristics in Botswana. For their identification, a heat wave is defined as a period when daily maximum temperatures exceed the normal maximum temperatures by 5 ^{0}C for at least five successive days. Four heat waves variables: (i) mean severity, (ii) mean frequency, (iii) mean duration, and (iv) mean number of heat wave days, have been estimated. Daily maximum temperature observational data for nine synoptic weather stations, which have been used in the study, were obtained from the Botswana Department of Meteorological Services. The stations had data records falling within the period 1959 to 2015 (56 years). The selected heat waves variables have been analysed for trends, whose statistical significance have been assessed using the Mann Kendall test. It has been found that the stations' mean severity and mean number of heat wave days (the more robust heat waves variables) generally had rising trends over the period 1959 to 2015. The Mann Kendall test revealed that two of the nine selected stations' mean severity had trends that were statistically significant at 10% significance level. It also revealed that a different pair of the selected stations had statistically significant trends in their mean number of heat wave days. The trends in the other stations' mean severity and mean number of heat wave days were not statistically significant. With regard to the trends in the mean duration and mean frequency (the less robust heat waves variables), the test indicated that they did not have statistically significant trends at the chosen level of significance.

Introduction

'**Heat wave hits Botswana!** The Department of Meteorological Services has warned that the prevailing weather conditions of hot temperatures are expected to continue until next week. Temperatures over the country are expected to reach maximums of between 36 and 40 ^{0}C. However temperatures are eventually expected to reduce over southern Kgalagadi District by 3 ^{0}C on October 11. The department therefore advises members of the public to take precautionary measures to protect themselves from these adverse weather conditions. These measures might include among others: Drink more water regardless of your activity level; avoid prolonged stay under the sun, if at all possible stay under the shade; protect yourself from the sun by wearing a wide-brimmed hat or umbrella. The department will keep monitoring the conditions, and will update the public accordingly' (*Daily News* 2015).

The above quote is just one of several heat waves warnings that the Botswana Department of Meteorological Services (BDMS) has been issuing through the media over the years, indicating that heat waves are common in Botswana. One might ask, what is a heat wave? There are several heat wave definitions found in scientific literature, some of which are the following. A heat wave is a period of exceptionally warm temperatures (Robinson 2001); it is a period of at least 3 consecutive days when the daily maximum temperatures exceed the 90th percentile during summer (Lyon 2009); it is summertime episodes with extremely high surface air temperatures lasting for several days (Lau and Nath 2012); it is a period in which the maximum temperatures are over the 90th percentile of the monthly distribution for at least three days (Capuano 2013). The World Meteorological Organisation (WMO) defines a heat

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wave as a period when daily maximum temperatures exceed the normal maximum temperatures by 5 °C for at least five consecutive days (Met Office 2015). This definition has been adopted by Met Office, and by the BDMS. It is also adopted by the present study. Defining a heat wave or heat waves is a necessary step in their identification procedure.

Heat waves are of interest to scientists and the general public as they have impacts on human health, society and the economy. For instance, heat waves create environmental conditions that allow a net increase in the geographical belt of vector-borne diseases such as Malaria (Martens *et al*. 1999; Ebi *et al*. 2005). During the season of transmission, they create conditions that are favourable to parasite and vector populations increase. While temperature is a crucial climatic element in the spread of vector-borne diseases such as malaria, it is well known that rainfall is also crucial. To minimize diseases linked to climatic factors, the Botswana government has over decades, through its various departments put in place a number of strategies. These strategies include carrying out of malaria campaigns mainly in the Ngamiland and Chobe Districts, and implementation of early warning systems that timely communicate extreme weather warnings such as heat waves (Letsholo 2015), which are based on numerical weather prediction models. In Botswana's agricultural sector, impacts of heat waves include crop failure (Setshwaelo 2001; Lima 2014), decrease in poultry production as heat waves cause heat stress resulting in decreased feed consumption and increased drinking of water (Moreki 2008). Impacts of heat waves on the agricultural sector pose a threat to food security. In the country's water sector, impacts of extreme temperatures include increase in evapotranspiration rates over open water bodies (Moalafhi *et al*. 2013).

It is generally accepted in the mainstream science that climate change is real (Houghton *et al*. 2001; eds. Pachauri & Reisinger 2007; Schaefer & Domroes 2009; Shongwe *et al*. 2009; Wolski 2009; Chou & Lan 2011; Field *et al*. 2012; Stock *et al*. 2013; Field *et al*. 2014; Zhang *et al*. 2015). Since climate change causes air temperatures to increase, it is likely that heat waves impacts in Botswana will increase in the future. Climate change does not only affect air temperatures, but it also affects other climatic elements such as precipitation. However, such elements are beyond the scope of this study.

Many regions of the globe experience heat waves, and they have impacts on their various sectors. In view of the impacts, several parts of the world have conducted heat waves studies. For instance, in the United States, Gaffen & Ross (1998) studied heat waves using historical data and found significant positive trends in their frequencies. Easterling *et al*. (2000) studied the characteristics of extreme high temperature events based on general circulation models, which projected more occurrences of heat waves toward the end of the twenty first century. Meehl & Tebaldi (2004) examined model data, which indicated that heat waves will be more intense, more frequent, and longer lasting in the last part of the twenty first century. Lau & Nath (2012) examined the characteristics of heat waves using reanalysis data and simulations by two general circulation models, and found that there were increases in heat wave severity, heat wave duration, frequency, and the number of heat wave days per year. In Europe, Beniston (2004) studied the 2003 European heat wave using both climatological data and model simulations, and concluded that such heat waves are likely to occur in the future with greater frequency. In Africa, Lyon (2009) used climatological data to evaluate the behaviour of heat waves in South Africa, and the results indicated that they will increase. In the same study, the author analysed models simulations, which also indicated that there is a shift toward higher heat wave occurrences. New *et al*. (2006) used historical data to examine trends in indices for temperature extremes over west and southern Africa (which include Botswana). Their results indicated that trends in daily temperature extremes were increasing. Regenmortel (1995) studied Botswana's temperature variations and their relation to changes in the southern hemisphere temperatures. The study indicated that Botswana temperatures increased in unison with global warming.

Based on the previous heat waves studies, the present study seeks to improve the understanding of heat waves characteristics in Botswana by assessing four heat wave variables: mean severity, mean frequency, mean duration and mean number of heat wave days. The previous studies that analysed Botswana temperatures did not focus on the above mentioned heat waves variables; hence they are the focus of the present study. This study is based on temperature climatological data for nine synoptic weather stations, obtained from the BDMS. Some of the data records that are used in the study stretch from 1959 (some years before Botswana gained independence in 1966) to 2015, which means they have data records lengths of more than 50 years. The study also investigates the statistical significance of trends in the data. The study is crucial to various sectors, primarily to the health sector, agriculture, water management, atmospheric scientists and to policy makers.

Materials and Methods

The climate of the study area - Botswana

Botswana is a land locked country located between latitudes 17 and 27 ^{0}S, and between longitudes 20 and 29 ^{0}E (Figure 1). It has a surface area of approximately 582000 km^2 (The Botswana National Atlas n.d.). Rainfall is low and erratic, and it occurs mainly during the rainfall season which stretches from October to March. It ranges between a maximum of 650 mm in Kasane in northern Botswana and a minimum of less than 250 mm in the southwest (Bhalotra 1987). The main reason why the country generally receives low rainfall is due to its location in the hinterland of the Southern African region, far away from the oceans which are the sources of moisture (Umoh 2005; Moses 2007). Mean monthly maximum temperatures range from 32 to 35 ^{0}C, but daily maximums can be as high as approximately 43 ^{0}C (Bhalotra 1987; Moses 2007). The highest maximum temperatures are experienced during the period October to March (rainfall season). The lowest mean monthly minimum temperatures are experienced in July, in the southwest. They range between 2 and 7 ^{0}C, but daily minimums can drop to below -5 ^{0}C.

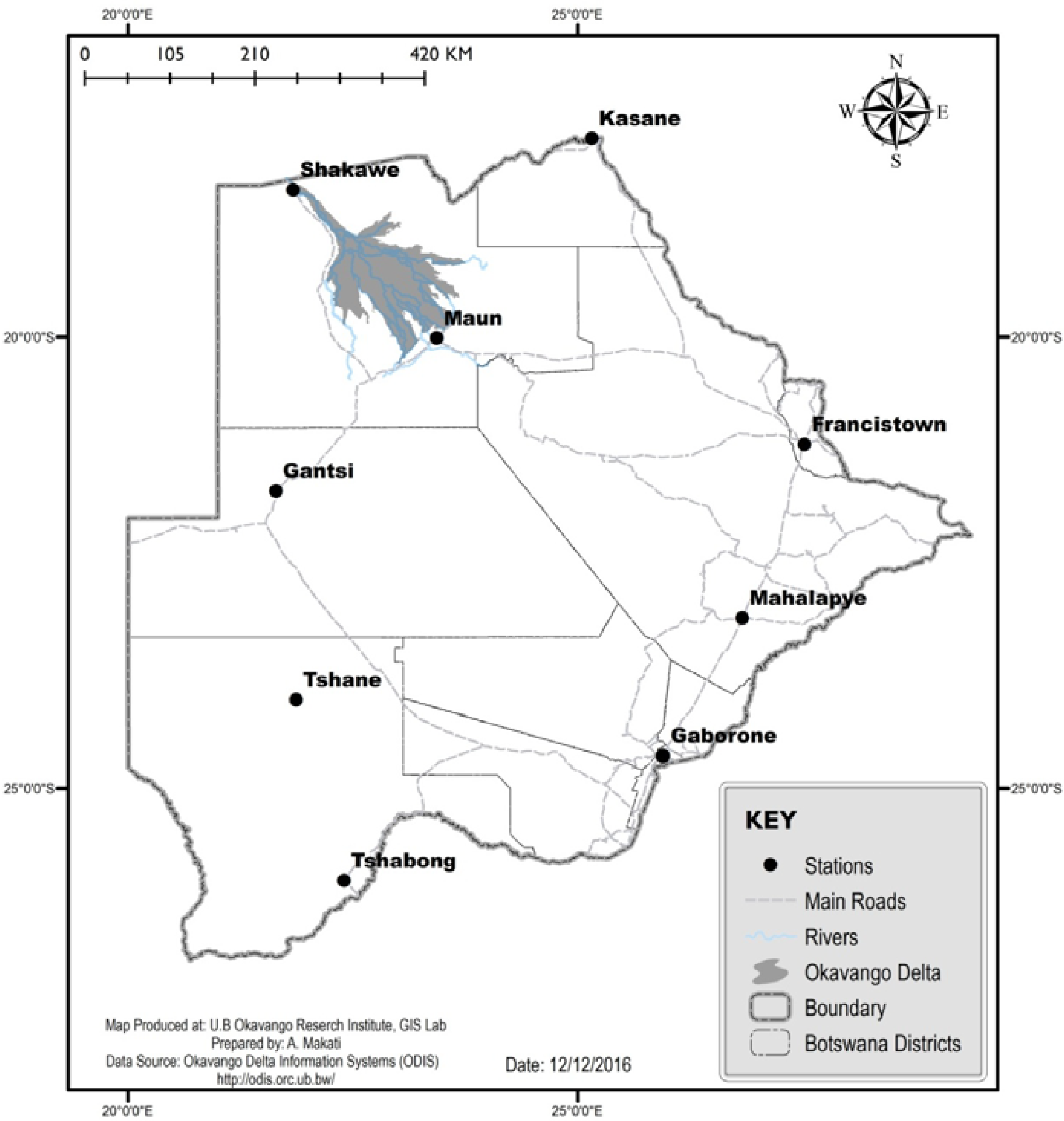
High temperatures are associated with slow moving synoptic scale medium level high pressure systems interacting with dry soils (Lau & Nath 2012; Nairn & Fawcett 2014). Since Botswana's climate is generally hot and semi-arid to arid, it means that the country's soils can be dry for several days or months, thus creating favourable conditions for occurrence of high temperatures. Synoptic scale weather systems that influence the country's weather conditions include the following: medium levels high pressure systems, cut-off lows, frontal systems, Inter Tropical Convergence Zone (ITCZ), the Atlantic Ocean high pressure system, the Indian ocean high pressure system, easterly troughs, westerly troughs and surface lows (Moses & Parida 2016).

Weather stations and the data

The country's weather observations are made by the BDMS, which has weather stations spread across the country. Before the country gained independence on 30th September 1966, there were only seven synoptic weather stations. Over the past 50 years, the BDMS has improved its weather stations network, by June 2016, there were seventeen synoptic weather stations spread across the country, twenty nine Automatic Weather Stations (AWS), and about seven hundred rainfall stations.

In this study, daily maximum temperature data for nine synoptic weather stations of the BDMS were selected for analysis. They were Tsabong, Gantsi, Francistown, Shakawe, Tshane, Mahalapye, Maun, Kasane and Sir Seretse Khama International Airport (SSKIA). SSKIA lies on the periphery of the country's capital city Gaborone, about 9.8 km to the north of the city centre. The locations of the selected stations are indicated in Figure 1, with SSKIA labelled as Gaborone so as to avoid clustering the map. The stations were selected for analysis based on the fact that they all had minimum data lengths of 30 years required for climate change studies. From the selected stations, Tsabong had the longest data record of 56 years (1959 to 2015), while SSKIA had the shortest data record of thirty years (1985 to 2015). The other stations had data records with lengths that varied between 30 and 56 years, but fell within the period 1959 to 2015. Only the data for the months October to March were chosen for analysis as they are the months in which the country experiences the hottest weather conditions. The data were quality checked through visual inspection. Minor typing errors were identified and corrected in consultation with the BDMS.

Figure 1: Location of the selected weather stations in Botswana



Identification of heat waves

As stated in the introduction, a heat wave is defined in this study as a period when daily maximum temperatures exceed the normal maximum temperatures by 5 ^{0}C for at least five consecutive days (Met Office 2015). The 5 ^{0}C above normal (1981-2010) is estimated in this study using a percentile based threshold, selected to be the 90th percentile (Russo *et al*. 2014). In this paper, heat waves are identified on the basis of daily maximum temperatures only. An event is identified as a heat wave when it meets the following conditions: daily maximum temperatures exceed the 90th percentile for at least five consecutive days, the mean temperature over the entire event also exceeds the 90th percentile, and the temperatures on each day of the entire event exceed the 75th percentile (Beniston 2004; Meehl & Tebaldi 2004; Lau & Nath 2012; Russo *et al*. 2014).

Estimation of heat waves variables

The paper primarily focuses on assessing the heat waves variables mean severity, mean frequency, mean duration and mean number of heat wave days (Changnon *et al*. 1996; Gaffen & Ross 1998; Kunkel *et al*. 1999; Easterling *et al*. 2000; Beniston 2004; Meehl & Tebaldi 2004; Hunt 2007; Lyon 2009; Lau & Nath, 2012; Russo *et al*. 2014). Duration refers to the time span of the event, which has a minimum of at least five consecutive hot days according to the adopted heat wave definition. Severity refers to the mean temperature over the identified event. Frequency refers to the number of heat wave events per year. Mean duration, mean severity and mean frequency are estimated as yearly averages over time intervals of ten years. The mean number of heat wave days is estimated as the product of the mean duration and the mean frequency.

The Mann Kendall test

To test for statistical significance of trends in the data, the Mann Kendall test (Kendall 1975; Batisani & Yarnal 2010; Myronidis *et al*. 2012) is used. With this test, it is not necessary for the data to conform to any particular distribution, and the test statistics are invariant to transformations.

Results and Discussion

Analysis of the selected heat waves variables

Table 1 contains the 75th and the 90th percentiles which were used in the identification process of heat waves. Also contained in the table are the highest daily maximum temperatures for the selected stations (ranging between 41.0 ^{0}C in Tshane and 43.0 ^{0}C in Tsabong), the mean daily maximum temperatures and their standard deviations. The estimated values of the selected heat waves variables, i.e., mean severity, mean frequency, mean duration and the mean numbers of heat wave days are given in Tables 2 to 4. Previous studies have indicated that the mean duration and the mean frequency are less robust (Frich *et al*. 2002; Russo *et al*. 2014), while the mean number of heat wave days and the mean severity are more robust (Lau & Nath 2012). The more robust heat waves variables are shown in Figures 2 to 4. On these figures, the mean severities are depicted by the graphs (a), (c) and (e), while the mean numbers of heat wave days are depicted by the graphs (b), (d) and (f). It should be noted that the time intervals that are less than ten years (see Tables 2 to 4 towards the end of each station's data record) are not included on the horizontal axis of Figures 2 to 4. This is to ensure that the heat waves variables are assessed over equal time intervals on the graphs. The linear trend lines plotted on the graphs indicate that both the mean heat wave severity and the mean number of heat wave days had increasing trends during the period 1959 to 2015 (approximately 50 years). The rising trends are in agreement with the findings of other heat wave studies conducted in other parts of the world (e.g., Gaffen & Ross 1998; Easterling *et al*. 2000; Houghton *et al*. 2001; Beniston 2004; Meehl & Tebaldi 2004; eds. Pachauri & Reisinger 2007; Lyon 2009; eds. Field *et al*. 2012; Lau & Nath 2012; Capuano *et al*. 2013; eds. Stock *et al*. 2013; eds. Field *et al*. 2014; Russo *et al*. 2014). Analysis of the less robust heat waves variables, i.e., the mean duration and the mean frequency (Tables 2 to 4), did not show clear directions of the trends over the past 50 years.

Table 1: Period of the data, highest daily maximum temperature (Highest T_{max}), mean daily maximum temperatures (mean T_{max}), 90th percentile (T_{90}), 75th percentile (T_{75}) and standard deviations (σ) of daily maximum temperatures

Station	Data Period	Highest T_{max} (^{0}C)	Mean T_{max} (^{0}C)	T_{90} (^{0}C)	T_{75} (^{0}C)	σ (^{0}C)
Tsabong	[λ]1959- [d]2015	43.0	33.0	37.7	36.0	3.8
Gantsi	[λ]1960 - [d]2015	42.2	32.5	36.9	35.7	3.5
Francistown	[λ]1961 - [d]2015	42.1	31.1	36.0	34.0	4.0
Shakawe	[λ]1961 - [d]2015	42.1	32.4	36.7	34.8	3.4
Tshane	[λ]1961 - [d]2015	41.0	33.0	36.9	35.2	3.5
Mahalapye	[λ]1962 - [d]2015	42.4	30.9	35.8	33.7	4.0
Maun	[λ]1965 - [d]2015	41.7	33.0	37.4	35.6	3.4
Kasane	[λ]1982 - [d]2015	41.4	31.8	36.3	34.2	3.4
SSKIA	[λ]1985 - [d]2015	41.5	31.4	36.0	34.0	3.7

Table 2: Heat waves variables (mean duration, mean severity, mean frequency, mean intensity and mean number of heat waves days) for Tsabong, Gantsi and Francistown

Station	Period	Mean Duration (days)	Mean Severity (^{0}C)	Mean Frequency per year	Mean no of heat waves days per year
Tsabong	[λ]1959 - [d]1969	8.2	38.0	2.6	21.3
	[λ]1969 - [d]1979	9.0	37.9	2.1	18.9
	[λ]1979 - [d]1989	8.3	38.2	2.4	19.9
	[λ]1989 - [d]1999	8.8	38.3	2.3	20.2
	[λ]1999 - [d]2009	7.1	38.3	3.0	21.3
	[λ]2009 - [d]2015	8.1	38.0	2.0	16.2
Gantsi	[λ]1960 - [d]1970	6.9	37.6	2.1	14.5
	[λ]1970 - [d]1980	10.4	37.5	1.4	14.6
	[λ]1980 - [d]1990	8.2	37.7	1.8	14.8
	[λ]1990 - [d]2000	6.9	37.7	2.1	14.5
	[λ]2000 - [d]2010	6.6	37.6	2.3	15.2
	[λ]2010 - [d]2015	7.0	37.7	2.1	14.7
Francistown	[λ]1961 - [d]1971	6.0	37.2	1.4	8.4
	[λ]1971 - [d]1981	7.0	37.0	1.2	8.4
	[λ]1981 - [d]1991	6.5	37.3	1.3	8.5
	[λ]1991 - [d]2001	7.1	37.5	1.7	12.1
	[λ]2001 - [d]2011	6.5	37.8	1.8	11.7
	[λ]2011 - [d]2015	6.8	38.1	1.8	12.2

[λ] *October*, [d] *March*

Table 3: Heat waves variables (mean duration, mean severity, mean frequency, mean intensity and mean number of heat waves days) for Shakawe, Tshane and Mahalapye

Station	Period	Mean Duration (days)	Mean Severity (^{0}C)	Mean Frequency per year	Mean no of heat waves days per year
Shakawe	$^{\lambda}$1961 - ^{d}1971	8.8	38.0	1.2	10.6
	$^{\lambda}$1971 - ^{d}1981	9.3	37.9	1.1	10.2
	$^{\lambda}$1981 - ^{d}1991	6.9	38.0	1.6	11.0
	$^{\lambda}$1991 - ^{d}2001	8.2	38.2	1.7	13.9
	$^{\lambda}$2001 - ^{d}2011	8.1	38.1	1.8	14.6
	$^{\lambda}$2011 - ^{d}2015	8.9	38.2	1.6	14.2
Tshane	$^{\lambda}$1961 - ^{d}1971	6.9	37.6	1.9	13.1
	$^{\lambda}$1971 - ^{d}1981	6.9	37.9	1.8	12.4
	$^{\lambda}$1981 - ^{d}1991	6.8	37.9	2.1	14.3
	$^{\lambda}$1991 - ^{d}2001	6.9	37.9	2.0	13.7
	$^{\lambda}$2001 - ^{d}2011	6.8	37.8	2.1	14.3
	$^{\lambda}$2011 - ^{d}2015	6.2	38.0	2.0	12.6
Mahalapye	$^{\lambda}$1962 - ^{d}1972	5.6	37.7	0.8	4.5
	$^{\lambda}$1972 - ^{d}1982	6.1	37.1	0.7	4.3
	$^{\lambda}$1982 - ^{d}1992	6.3	37.7	0.7	4.4
	$^{\lambda}$1992 - ^{d}2002	5.8	37.6	0.8	4.6
	$^{\lambda}$2002 - ^{d}2012	7.0	38.1	1.0	7.0
	$^{\lambda}$2012 - ^{d}2015	7.0	38.2	1.1	7.7

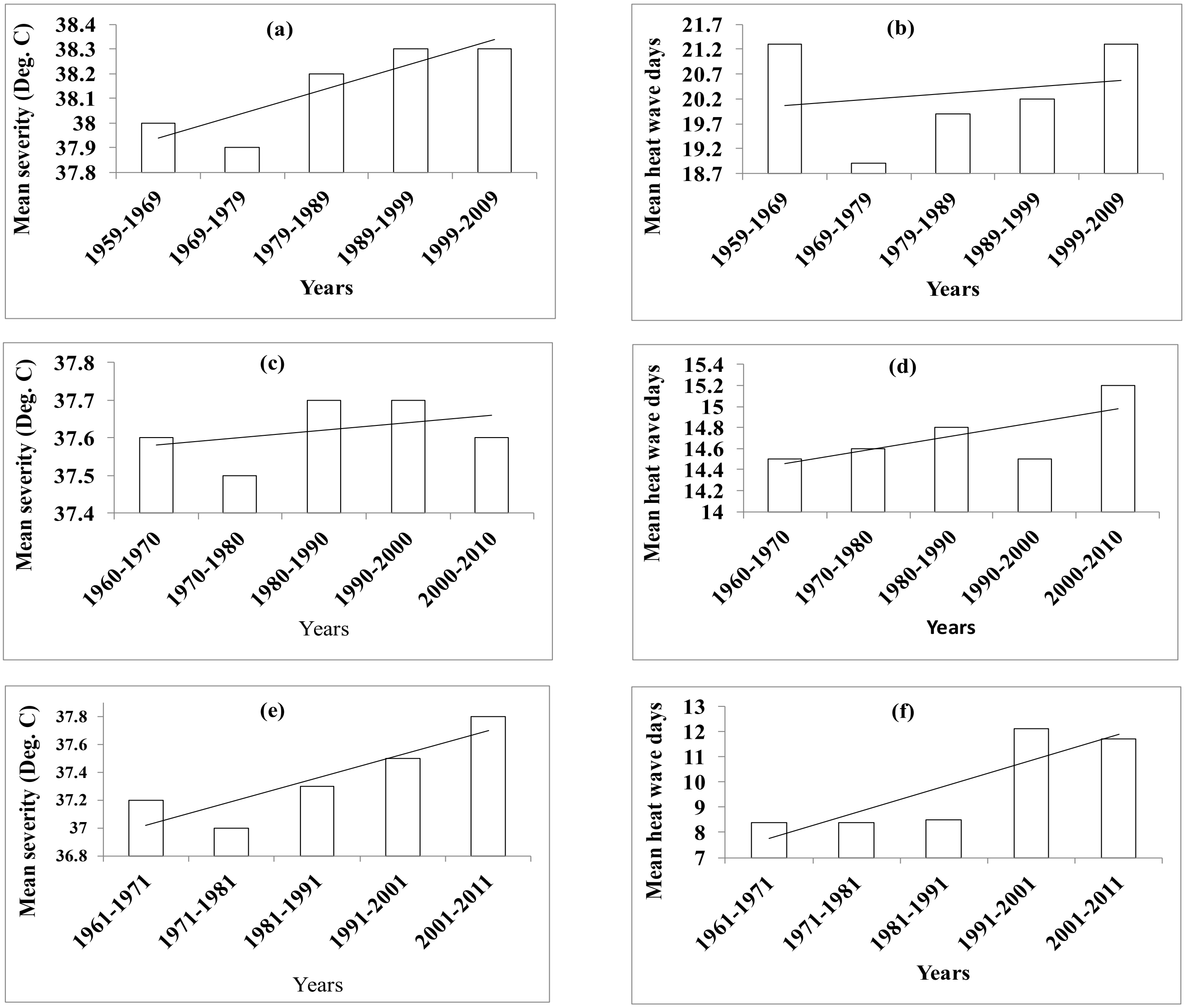
$^{\lambda}$ *October,* ^{d} *March*

Table 4: Heat waves variables (mean duration, mean severity, mean frequency, mean intensity and mean number of heat waves days) for Maun, Kasane and SSKIA

Station	Period	Mean Duration (days)	Mean Severity (^{0}C)	Mean Frequency per year	Mean no of heat waves days per year
Maun	$^{\lambda}$1965 - ^{d}1975	7.4	38.2	1.4	10.4
	$^{\lambda}$1975 - ^{d}1985	7.0	38.1	1.6	11.7
	$^{\lambda}$1985 - ^{d}1995	7.7	38.1	1.8	13.9
	$^{\lambda}$1995 - ^{d}2005	7.6	38.3	2.2	16.7
	$^{\lambda}$2005 - ^{d}2015	6.5	38.2	2.4	15.6
Kasane	$^{\lambda}$1982 - ^{d}1992	6.5	37.4	1.2	7.8
	$^{\lambda}$1992 - ^{d}2002	6.7	37.5	1.1	7.4
	$^{\lambda}$2002 - ^{d}2012	6.0	37.5	1.6	9.6
	$^{\lambda}$2012 - ^{d}2015	5.7	37.5	1.7	9.7
SSKIA	$^{\lambda}$1985 - ^{d}1995	5.9	37.6	1.5	8.9
	$^{\lambda}$1995 - ^{d}2005	6.5	37.8	1.3	8.5
	$^{\lambda}$2005 - ^{d}2015	6.2	37.8	1.5	9.3

$^{\lambda}$ *October,* ^{d} *March*

Figure 2: Mean heat wave severities for Tsabong, Gantsi and Francistown are depicted by the graphs (a), (c) and (e) respectively, while the mean numbers of heat wave days for the same stations are depicted by the graphs (b), (d) and (f). The heat waves variables are averaged over time intervals of 10 years.



The Mann Kendall test

Running the Mann Kendall test on the more robust heat waves variables plotted in Figures 2 to 4 yielded the results given in Table 5. The magnitudes of the Mann Kendall statistic S are small and positive for all the stations, confirming that the linear trends displayed in Figures 2 to 4 are increasing, but are generally weak (Kendall 1975). The test statistics (Z) of the Mann Kendall test indicate that over the period 1959 to 2015, the trends in the mean severity for Francistown and Tshane, and in the mean number of heat waves days for Maun and Shakawe are statistically significant since they (Z values) are greater than the critical values at 10 % significance level (α=0.1). For the other stations, the trends in the mean severity and the mean number of heat waves days are statistically insignificant at the stated significance level. Concerning the less robust heat waves variables (mean duration and mean frequency), their trends were found to be statistically insignificant at the selected 10 % significance level; hence their Z values are not reported in this paper.

Figure 3: Mean heat wave severities for Shakawe, Tshane and Mahalapye are depicted by the graphs (a), (c) and (e) respectively, while the mean numbers of heat wave days for the same stations are depicted by the graphs (b), (d) and (f). The heat waves variables are averaged over time intervals of 10 years.

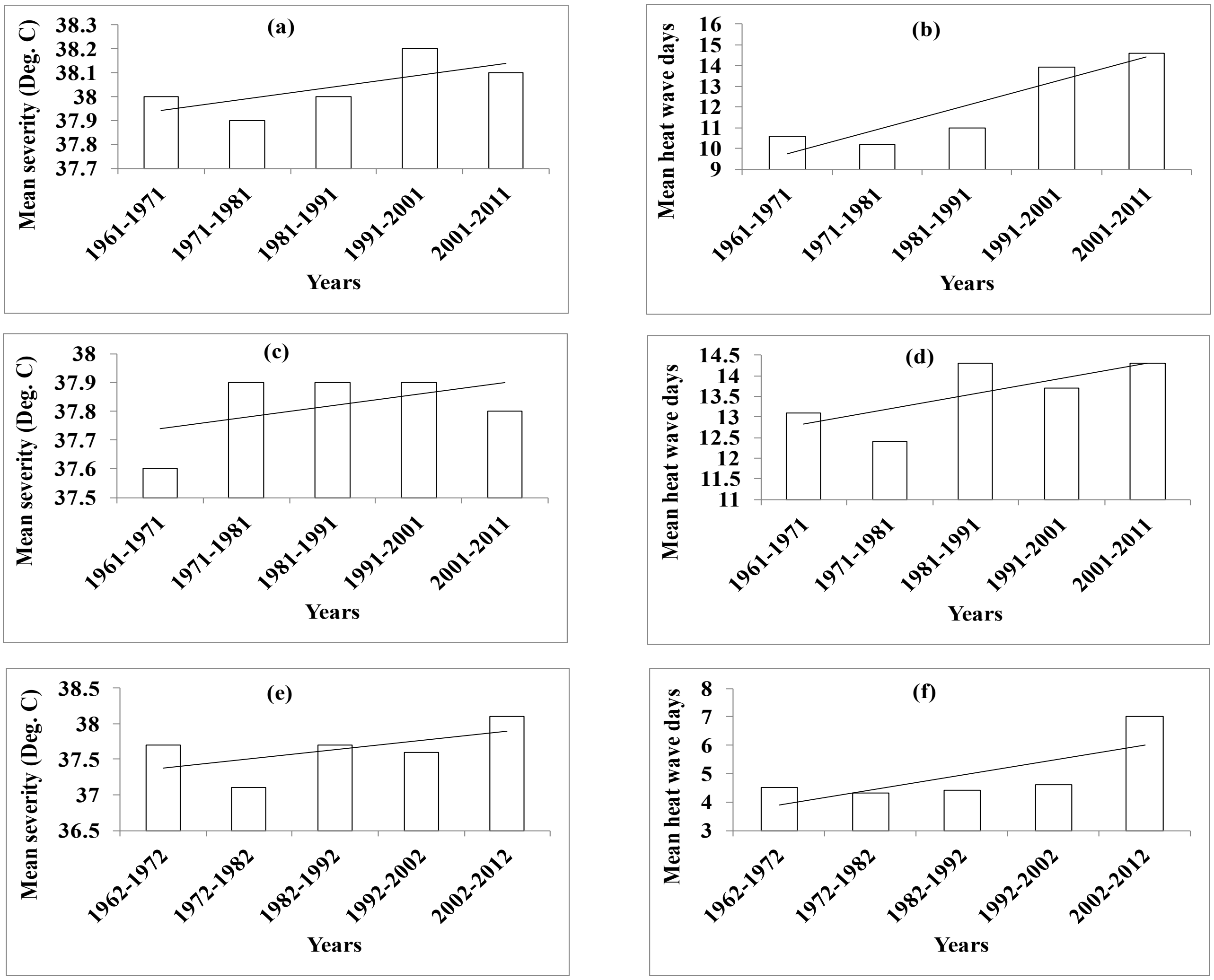
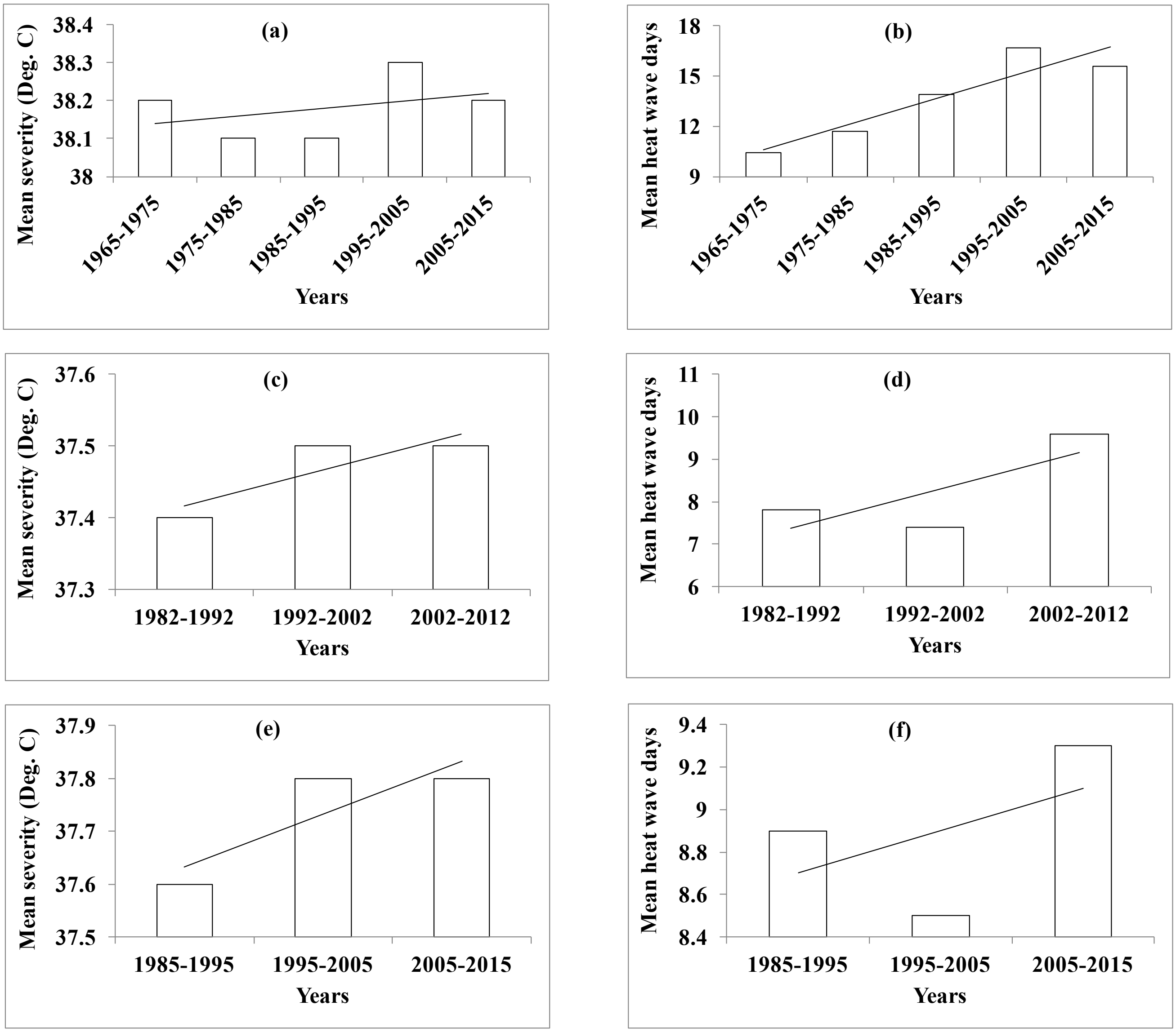


Table 5: Mann Kendall statistic S, test statistics Z, critical value (c-value) for the mean severity and mean number of heat waves days

Station	Mean severity				Mean number of heat wave days			
	S	Z	c-value at α=0.1	Result Significant (Yes/No)	S	Z	C-value at α=0.1	Result Significant (Yes/No)
Tsabong	7	1.516	1.645	No	3	0.505	1.645	No
Gantsi	2	0.261	1.645	No	3	1.011	1.645	No
Francistown	8	1.715	1.645	Yes	8	1.516	1.645	No
Shakawe	5	1.011	1.645	No	8	1.715	1.645	Yes
Tshane	7	1.664	1.645	Yes	5	1.011	1.645	No
Mahalapye	3	0.505	1.645	No	6	1.225	1.645	No
Maun	2	0.261	1.645	No	8	1.715	1.645	Yes
Kasane	3	0.894	1.645	No	4	1.019	1.645	No
SSKIA	3	0.894	1.645	No	3	0.722	1.645	No

Figure 4: Mean heat wave severities for Maun, Kasane and Sir Seretse Khama International Airport (SSKIA) are depicted by the graphs (a), (c) and (e) respectively, while the mean numbers of heat wave days for the same stations are depicted by the graphs (b), (d) and (f). The heat waves variables are averaged over time intervals of 10 years.



Conclusion

Heat waves have been defined, and have been identified solely on the basis of daily maximum temperatures. These weather phenomena have impacts on human health, society and the economy. Their characteristics in Botswana have been studied by assessing four heat wave variables: mean severity, mean frequency, mean duration and mean number of heat wave days. The results indicate that the more robust heat waves variables (mean severity and mean number of heat waves days) had rising trends over the past 50 years (1959 to 2015). This is consistent with the results of similar studies that were carried out in different geographical locations of the world. Using the Mann Kendall test, trends in the mean severity for Francistown and Tshane, and in the mean number of heat wave days for Shakawe and Maun, have been found to be statistically significant at 10% level of significance. Trends in the mean severity and mean number of heat wave days for the other stations were not statistically significant at the above mentioned significance level.

Pertaining to the stations' less robust heat waves variables (mean duration and mean frequency), the Mann Kendall test revealed that their trends were not statistically significant at 10% significance level. The statistically significant rising trends in the heat waves variables can be attributed to climate change. This implies that heat waves impacts are likely to increase in the future unless mitigation measures of these trends are put in place. The results of the study are crucial mainly to those in the health sector, agriculture, water management, atmospheric science and policy formulation. It is recommended that the results should be taken into consideration in planning programmes. It is also recommended that similar future studies should consider using climate models projections to study heat waves characteristics in the last part of the 21st century. This would assist in the formulation of appropriate response strategies.

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