Spatiotemporal Analysis of Heat Waves in Jordan

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Abstract

Heatwaves are durations of relatively extreme high temperatures. The literature presents multiple methods and criteria of identifying heatwaves based on Temperature exceedance parameter, and a duration parameter. All these presented criteria when applied result in different characteristics measures of heatwaves. Heatwaves are usually studied to identify their impact on one of the affected sectors (Human health, Energy consumption, Ecological conditions, urban air quality, environmental conditions, and any other sector that might be impacted). However, the literature provides little assistance in selecting which criteria to use for which purpose. In this work the idea of using different criterion based on the impacted sector being studied was introduced, we also defined a best fit heatwave criterion to assess the impact of heatwaves on human health based on the existing literature. We then use this criterion to identify heatwaves in 13 stations in Jordan and study the spatial, temporal, and spatiotemporal distributions and development of these heatwaves throughout the study duration (1970-2005). The result of the study shows a dramatic increase in heatwaves characteristics across Jordan. The area subjected to the highest change was the Jordanian capital (Amman), with an increase of 7 folds in number of heatwave days per year, 3 folds in number of heatwaves per year, and a 10% increase in the average temperature in the yearly maximum heatwave. The trends showed no signs of slowing down in the heatwaves' characteristic change. When projected Amman is expected to have 41 heatwave days and 9.8 heatwaves per year by 2050.

1 Introduction

Global warming and climate change have been attributed to the increasing consumption of fossil fuel and deforestation, resulting in a continuous increase in the atmosphere's greenhouse gases (Houghton, 2005). This change has had some undeniable effects on the environment and multiple aspects of human lives (Li et al., 2021). As the stability of the Biosphere ecological and physical systems are some of the main factors affecting the sustainability of human health on the planet (World Health Organization, 2003), the impact of climate change on human health becomes evident.

The gradual increase in overall temperature (maximum, minimum) year-round has had a clear impact on the characteristics of extreme weather conditions, increasing its severity and adversity (Mirza, 2003). Heatwaves are one of these extreme weather conditions, as they are durations of relatively extreme high temperature having a negative impact on human health, ecological conditions, urban air quality, and environmental conditions (Li et al., 2021). During the last 100 years, many extreme heatwaves have occurred throughout the globe (Trigo et al., 2005; Karoly, 2009; Barriopedro et al., 2011). The recorded heatwaves have had significant negative impacts on human health, increased energy and water demand, increased stress on the infrastructure, and caused natural and environmental disasters through the resulting wildfires (Perkins, 2014). These records agree with the studies on heatwave's impact, which suggest that heatwaves have an impact on human mortality and morbidity (Knowlton et al., 2009). Other studies have found that heatwaves have an impact on daily energy requirement during peak hours and throughout the 24-hours cycle, and the daily water demand (Hatvani-Kovacs et al., 2016).

The diverse and significant impacts of heatwaves on human's sustainability and day to day life have led to the heatwaves' changes becoming a primary indicator in assessing the impact of climate change (Jones et al., 2018; Tebaldi & Lobell, 2018; Warshaw, 2018). The temporal increase in heatwave's characteristics due to climate change had already been observed and recorded (Perkins et al., 2012). These recorded and expected impacts make understanding and analyzing heatwaves a global research priority.

While climate and heatwave changes are global issues, the impact of these changes vary based on the country's resources and development. Studies have shown that heatwaves in developing countries will have a much higher impact on the public health and infrastructure (Luo and Lau, 2019; Russo et al. 2019; Zhao et al. ,2015). This increases the importance of studying heatwaves' development for a developing country with limited resources like Jordan.

Future models predict that the temperature in Jordan will increase by 2.5°C to 5°C by the end of the century, while the annual precipitation is expected to drop by 10–37% (Abdulla, 2020). Even the most optimistic scenarios predict that unless the issue is tackled by proper planning, scheduling, and implementation, only a grim and an unsustainable future is lurking ahead.

There are multiple available detection criteria for heatwaves that specify different temperature thresholds values (fixed value, percentile value), different threshold calculations for percentile values (seasonal, yearly, and moving window), using maximum or mean temperature, and number of exceedance days (Li et al. 2015). All the definitions available in the literature are possible ways of detecting heatwaves, however the resulting heatwaves following each method are different. Different results lead to different correlations and trend significances which can change the interpretation of the climate change and heatwaves impact based on the type of impact being studied. We suggest that different heatwave definitions will be most suitable for different impacted sectors studies. That means that a definition might show the best correlation with wildfires while another will have best correlation with spikes in energy consumption, and so on. This unique look into the definition and correlation of heatwaves' impact to different sectors was not suggested or discussed in the literature before to the best of our knowledge. This work will focus specifically on identifying the heatwave definition with the best correlation with human health impact. In this work we will identify and select the criteria which have shown the highest impact and correlation with human health through the available literature. A heatwave detection criterion that is formulated to identify heatwaves with the highest human health impact and correlation.

Understanding heatwaves development and trend changes due to climate change is a key factor in mitigating their impact, while having an accurate future heatwave projection can be a key factor in resources distribution and allocation during heatwaves. This work focuses on the analysis and understanding of heatwaves spatial and temporal distribution and development in Jordan using the heatwave detection criteria of highest impact on human health, as this work has never been done before.

2 Data And Methods

2.1 Station's Locations

Records of daily maximum and minimum temperature were collected for 13 evaporation stations, the data locations were selected based on data quality and availability, Table 1 summarizes the stations and their available used data in Jordan. The stations were carefully selected so that they represent all of Jordan's climatic and demographic zones, while maintaining a high quality (more than 95% of daily data is available), the few missing days were populated based on the least square method of nearby stations and CORDEX historical data. For 10 stations the data was collected from the Jordanian Ministry of Water and Irrigation recorded through their distributed evaporation stations. For the other 3 stations, the data was collected from CORDEX historical database at the coordinates of existing evaporation stations due to Ministry's data availability issues. Refer Table 1 for stations names, locations, and source of data. Figure 1 shows the stations map location and spatial distribution. We have selected a higher number of stations in locations with high population densities to account for rapid climatic spatial changes due to the urban heatwave island (UHI) effect (Yao et al., 2021).

Table 1
Stations Numbers, Names, data collection source, first year of available data, and last year of available data. (Prepared on MS Office)

No	Station name	Data Source	Start Year	End Year
1	Amman	Ministry of Water and Irrigation	1971	2005
2	Baqura	Ministry of Water and Irrigation	1970	2005
3	Irbid	Ministry of Water and Irrigation	1971	2005
4	Mafraq	Ministry of Water and Irrigation	1971	2004
5	Ramtha	Ministry of Water and Irrigation	1976	2005
6	Rass Muneef	Ministry of Water and Irrigation	1977	1996
7	Wadi Dulail	Ministry of Water and Irrigation	1971	2004
8	Aqaba	Ministry of Water and Irrigation	1987	2010
9	H4	Ministry of Water and Irrigation	1968	2012
10	H5	Ministry of Water and Irrigation	1968	2012
11	Karak	CORDEX	1971	2004
12	Ma'an	CORDEX	1971	2004
13	Wadi Musa	CORDEX	1971	2004

2.2 Definitions.

Heatwaves have had various definitions introduced in the literature; the identification of heatwaves is based on exceeding a temperature threshold for a continuous specific number of days. This work identifies the heatwave selection criteria based on its correlation with human health as HHH (Heatwave Impacting Human Health).

1. Temperature data set: The temperature thresholds have been identified in the literature based on Mean or maximum temperature (Xu, 2016). This work uses the mean temperature for the identification of heatwaves, as climate's change impact on temperature in general affects minimum temperature more than it affects the maximum temperature (Alexander et al., 2006; Donat & Alexander, 2012), and as the most important factor affecting heatwaves impact on humans is the number of days with no relief, which requires high nighttime temperature as well (Karl & Knight, 1997).
2. Exceedance percentile and duration: this work adopts the heatwave detection criteria as the exceedance of the 90th percentile temperature for 2 more consecutive days. Duration of 2 days of exceedance and for a 90th percentile cutoff point (Tong et al., 2014). This criterion is selected for identifying a heatwave based on the observation by (Sun et al, 2014a) that emergency department visits, and emergency ambulance dispatches were directly impacted and showed correlation with the 90th percentile heatwaves for 2 days.
3. Threshold value calculation: This work uses the definition of a 15-day moving window (TX90pct) (e.g., Fischer and Shär, 2010). Using a constant value or seasonal exceedance threshold will result on most of the heatwaves occurring at the highest temperature months (beginning of august in our case). However, studies have shown an increase in vulnerability of human health in early summer temperature extremes (Sheridan et al., 2019; Steadman, 1984; Ng et al., 2014; Fuhrmann et al., 2011; Zaninović & Matzarakis, 2014). These extremes can only be identified using a window approach of calculating heatwaves, as the temperature of each day is compared with its 15 days average (one week before and one week after) for all years In this work the threshold values are calculated using a local probability density function for the 15 days moving window centered around the day being studied (Della-Marta et al., 2007), this method will allow for relative extreme temperature anomalies detection regardless of the testing date.

Using these criteria, we defined HHH as any heatwave identified using mean temperature that exceeds the 90th percentile of a moving average probability function for 2 or more consecutive days. The HHH identified are then analyzed by calculating their spatiotemporal characteristics.

Heatwave yearly duration (YD) refers to the number of yearly heatwave days and not to the average heatwave length, so that it highlights the change in the total heatwave days per year. Heatwave frequency (HF) refers to the number of heatwaves occurring each year. Yearly heatwave maximum average intensity (HMAI) refers to the maximum calculated average temperature amongst all the heatwaves occurring every year. HMAI is used instead of average heatwave intensity (HWM) (Perkins et al., 2012) to prevent the data from being misrepresented due to increase of heatwaves in relatively colder months. Duration slope (DS) refers to the slope of the trend line between years of measurement and the total number of

heatwave days per year. Frequency slope (FS) refers to the slope of the trend line between years of measurement and number of heatwaves each year. Intensity slope (IS) refers to the slope of the trend line between years of measurement and maximum heatwave average intensity.

2.3 Daily Heatwave Thresholds.

The daily $T_{\max}$ and $T_{\min}$ for months of June-October (153 days) are extracted from the overall temperature data for each station. The data was then subjected to a logic and homogeneity tests ($T_{\max} > T_{\min}$, and removal of obvious outliers) (Moberg et al., 2006). No significant data homogenizing methods were used to alter the temperatures as the point of the study is to identify heatwaves (extreme temperature variations and outliers).

The mean temperature was then calculated for each date and analyzed using a costume made Python program. The code analyzes each date and calculates it's 90th percentile value based on a moving 15-day window (one week before and one week after each date). The selection of a moving window method instead of a seasonal method is to account for the variability in mean temperatures during the summer season (June-October). The threshold values are presented in Fig. 2. The selection of the moving average methods allows for calculating the thresholds for the duration in study except for the first and last week of the period (as no 15-day window will be available for these week). Which means that thresholds are calculated starting 8th June until 24 October.

The threshold's values tend to peak around the biggening of august, and dips down towards the other 2 directions (Fig. 2.). These results emphasize the importance of adopting a moving average definition of heatwaves (15 days moving average in this case), as if a seasonal threshold is calculated, the threshold comparison will reflect an overall temperature increase period rather than an aggressive variation (Della-Marta et al., 2007).

Notice that a heatwave happening during June or July for example will have a lower average intensity, which will lower the overall heatwave average intensity if simply calculated. For that reason, defining and adopting the HMAI value instead of heatwave overall average intensity allows for a more accurate data representation. as the increasing number of heatwaves will affect the average intensity by increasing the number of heatwaves in the relatively colder months (June, July, September, and October) which in turn will create a misleading representation of the heatwave intensity change. While the HMAI singles out the heatwave with the maximum average temperature during every specific year, creating a clearer representation of the magnitude of change.

2.4 Identifying Heatwaves

The moving window method calculates a single set of daily threshold values for each station, from 8th of June until 24th October. This set of values is then compared to the daily mean temperature readings to identify incidents of exceedance. Whenever a threshold value is exceeded for 2 or more consecutive days, a heatwave is identified and recorded. Heatwave days, temperatures, dates, heatwave start, end dates,

duration, and temperature volumes (summation of all heatwave days mean temperatures) are then calculated.

Heatwave identification sample for Amman station in the year 2002 is presented in Fig. 3. The sample shows the calculation done in this work (15 days window), compared to the constant threshold calculation method. As can be seen from Fig. 2 the constant threshold method's readings are concentrated at the beginning of august (measuring overall average temperature increase), while the 15-day window method creates a more accurate representation of the fluctuation as the threshold value varies based on the period's average temperature.

3 Results

3.1 Heatwaves Temporal Analysis

The process of identifying heatwaves is repeated for all the 13 stations included for all years (based on available years for each station). DY, HF, and HMAI are then calculated for each station yearly, then plotted against the timeline of measurements. A sample of the process is presented in Fig. 4.

For stations having years with no heatwave days, the DY and HF values were recorded as zero for the time series in the development of trends. HMAI in the other hand was simply omitted from the time series data when the year had no heatwaves (as per definition it is the highest average intensity among heatwaves per year). Incorporating HMAI as zero however will result in false data representation.

The data was then analyzed using the non-parametric Mann-Kendall trend test to identify the significance of trends (Table 2).

Table 2

Mann-Kendal non-parametric test significance values and thresholds for time series analysis of DY, HF, and HMAI. DY-Z refers to the statistical Z value calculated using the Mann-Kendall test for the trend line of the number of yearly heatwave days plotted against the study duration. HF-Z refers to the statistical Z value calculated using the Mann-Kendall test for the trend line of the number of heatwaves per plotted against the study duration. HMAI-Z refers to the statistical Z value calculated using the Mann-Kendall test for the trend line of the average intensity of the most intense yearly heatwave plotted against the study duration. (MS Office)

Station	DY-Z	HF-Z	HMAI-Z	Z ($\alpha = 0.05$)	Z ($\alpha = 0.01$)	Z ($\alpha = 0.001$)
Amman	3.676	3.743	2.783	1.96	2.576	3.291
Baqura	2.528	3.312	1.477	1.96	2.576	3.291
Irbid	2.513	2.042	1.264	1.96	2.576	3.291
Mafrq	2.136	2.086	1.534	1.96	2.576	3.291
Ramtha	1.415	1.198	0.652	1.96	2.576	3.291
Rass Muneef	0.794	1.128	-0.474	1.96	2.576	3.291
Wadi Dulail	2.644	3.045	2.371	1.96	2.576	3.291
Aqaba	0.474	0.787	1.410	1.96	2.576	3.291
H4	2.803	2.169	2.102	1.96	2.576	3.291
H5	2.018	2.205	1.131	1.96	2.576	3.291
Karak	1.356	2.038	2.351	1.96	2.576	3.291
Maan	1.325	1.045	1.294	1.96	2.576	3.291
Wadi Musa	1.471	1.186	0.790	1.96	2.576	3.291

Whenever the Z value for each characteristic is exceeding the $Z(\alpha = 0.05)$, $Z(\alpha = 0.01)$, and $Z(\alpha = 0.001)$ the time series has a significant trend at 95%, 99%, and 99.9% confidence intervals respectively. The data presented in Table 2 can be summarized as below:

- **DY:** only one station shows significant trend at 99.9% confidence interval, 2 stations show significant trend at 99% confidence interval, and 4 stations show significant trend at 95% confidence interval while 6 stations show no significant trend at 95% confidence interval.
- **HF:** 2 stations show significant trend at 99.9% confidence interval, 1 station show significant trend at 99% confidence interval, and 5 stations show significant trend at confidence interval of 95% while 5 stations show no significant trend at 95% confidence interval.
- **HMAI:** 1 station show significant trend at 99% confidence interval, and 2 station show significant trend at 95% confidence interval while 10 stations show no significant trend at 95% confidence interval.

Not only is the data presenting a clear positive trend, but it presents an increase in uncertainty as well (represented by the increase of fluctuations of readings away from the trend line).

The resulting graphs for each station represent the temporal changes in heatwaves' characteristics for each station location. Not all stations data records had the same start and finish dates (Table 1), so a trend line was extracted for each station and used to calculate average values to extend all data results to cover all the study period (1970–2005). The yearly magnitude in change was then plotted in Fig. 5. The results show that there is a clear increase trend that governs all the temporal changes in heatwave's characteristics (except for HMAI in Rass Muneef). The results comply with the expectations of an increase in heatwaves characteristics due to climate change represented in the literature (Min et al., 2011; Intergovernmental Panel on Climate Change, 2012; Coumou and Rahmstorf, 2012).

All stations show positive trends for DY and HF, and a positive trend in HMAI for all stations except for Rass Muneef. These trends represent the overall impact of climate change on heatwave's characteristics development in Jordan in the period of the study (1970–2005).

To have a clear and an easy to comprehend change comparison amongst stations, the values represented by these trend lines calculated for the years 1970 and 2005 were extracted instead of the actual reading values (to avoid high fluctuation years misrepresenting the actual data trends and provide duration homogeneity). DY, HF, and HMAI are calculated for the year 1970, then recalculated for the year 2005, the difference of the calculated values for these years are presented in Table 3. The table summarizes the overall changes in the heatwave characteristics values through the study period (1970–2005). While all the heatwave characteristics show a positive trend (except for Rass Muneef), the magnitude of change is variable throughout the country.

Table 3

change in heatwave characteristics in Jordan during the study period (1970–2005). Increase in Dy represent the total increase of the number of yearly heatwave days through the study duration (1970–2005). Increase in HF represents the total increase in the number of yearly heatwaves through the study duration. Increase in HMAI represents the increase in the average intensity of the most intense yearly heatwave in Celsius. (MS Office)

Station	Increase in DY (Days)	Increase in HF (Heatwaves)	Increase in HMAI (Celsius)
Amman	+ 16.95	+ 3.80	+ 2.79
Baqura	+ 14.23	+ 4.19	+ 1.88
Irbid	+ 9.93	+ 2.32	+ 0.65
Mafrq	+ 11.54	+ 2.66	+ 1.10
Ramtha	+ 9.75	+ 1.81	+ 0.68
Rass Muneef	+ 1.98	+ 1.17	-0.62
Wadi Dulail	+ 14.99	+ 3.76	+ 2.11
Aqaba	+ 8.85	+ 1.65	+ 1.91
H4	+ 16.43	+ 2.19	+ 1.52
H5	+ 10.98	+ 1.92	+ 0.91
Karak	+ 5.18	+ 2.53	+ 2.12
Maan	+ 5.88	+ 1.69	+ 1.75
Wadi Musa	+ 4.73	+ 1.83	+ 0.71

The results presented in Table 3 show the impact of climate change on the heatwaves' characteristics in Jordan during the study duration (1970–2005). The magnitude of change in heatwaves' characteristics is variable based on location. The area that experienced the highest increase was Amman with an overwhelming increase of 7 folds in number of heatwave days per year, 3 folds increase in number of heatwaves per year, and 10% increase in the average temperature of the most intense yearly heatwave during the warm season.

The results confirm that climate change has already changed and suggests that it will continue to change the country's temperatures profile distribution. The trend of increase in all heatwave characteristics was best fitted to a linear model. While the data show's various local fluctuations, the overall trend average clearly follows a linear increasing trend, which implies that the climate change's impact on heatwave characteristics is showing no signs of slowing down.

3.2 Heatwave's Spatial Analysis

To identify the different spatial heatwave's response to climate change, heatwave's characteristics heatmaps are then prepared for the YD, HF, and HMAI (ArcGIS heatmaps are prepared using IDW tool with a variable radius) for the year 1970 vs 2005. The 1970's in comparison with the 2005's heatwaves characteristics spatial distribution in Jordan (trend line values are inserted to avoid high fluctuation years) (Fig. 6).

The results presented in Fig. 6 proves that not only is climate change affecting heatwave characteristics change at varying rates throughout the spatial distribution in Jordan, but each individual characteristic is responding differently to climate change even at the same station.

3.3 Heatwave's Spatiotemporal Analysis

To create a spatiotemporal representation of climate change impact on each of the heatwave's characteristics, the slope of the three trendlines (DS, FS, IS) for each station is extracted through the trend line analysis in section 3.1. The resulting slopes were presented in a single heatmap for each characteristic. Allowing this heat map to present spatial distribution of temporal heatwaves' characteristics change (Fig. 7). The resulting heat maps represent the change trajectory of Jordan's heatwaves. As all the trend lines followed created a linear average, these maps suggest a future change in Jordan's climatic zones.

The heatmaps in Fig. 7 clearly show the extremely variable impact of climate change on the heatwave's characteristics based on location. The overall rate of change in heatwaves characteristics is concentrated in Amman (has the highest DS, FS, and IS). Which shows the correlation between population density (Amman has 42% of the Jordanian population) and rate of change in heatwave characteristics. These results agree with the studies on the impact of UHI on the climate change characteristics (Yao et al., 2021).

4 Conclusion

In this work we have suggested a new way of looking at heatwave detection criteria and definitions based on the impact being studied. We have also formulated what we believe to be a best fit criteria and a definition of heatwave to best fit the measurement of impact on human health based on the available literature. The results of the study show the significance of increasing trendlines of heat wave characteristics. The results conclude that Jordan is experiencing a significant and an alarming change in heatwaves' characteristics spatial as well as temporal distribution especially in highly populated areas (Amman showed significant upward trend at 99.9% confidence interval). Based on the calculated and presented magnitude of change for the study period (1970–2005), Jordan is experiencing varying levels of heatwaves changes. The city experiencing the biggest impact in Jordan is none other than Jordan's capital (Amman), the city with 42% of the Jordanian population (Jordan's Department of Statistics), which when coupled with the expected public health, energy demand, water demand, and infrastructure's load impact predicts a challenging future that requires a thorough preparatory planning and resource allocation.

The temporal change in heatwaves' characteristics showed no signs of slowing down during the study period, as the characteristics temporal distribution followed a best fit linear trend line. We see no reason to expect that this increasing trend will slow down in the near future as climate change models do not predict slowing down in the climate change. If the change in heatwaves' characteristics persist in the same trajectory, Amman is expected to be experiencing an average of 41 days of heatwaves per summer season, with a maximum heatwave intensity average of 34.4 Celsius by the year 2050.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Authors Contributions

Author two is the research advisor of author one, author one is a master's student. All authors contributed to the study concept and design. Material preparation and data analysis were performed by Yazan Alwadi, while data collection was performed by Fayez Abdulla and Yazan Alwadi. The first draft of the manuscript was written by Yazan Alwadi, and Fayez Abdulla commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

All data used to generate the results was collected from The Jordanian Ministry of Water & Irrigation, and through CORDEX data sets (specific data collection in Table 1).

CORDEX data is publicly available, While Ministry's Data required official approvals to obtain.

Input and output data are available can be accessed through the following link:

<https://drive.google.com/drive/folders/1vurzm6DvSliE55-z7GCE7GNnBuyvqKnT?usp=sharing>

Conflict of Interest

Authors have no conflict of interest to declare

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Figures

Figure 1

Studied station's locations in Jordan. (ArcMap)

Figure 2

Daily 90th percentile calculated temperature thresholds for the studied 13 stations. T refers to the daily mean temperature in Celsius. Date refers to the day in summer season to which the threshold value is calculated. Graph represents the 90th percentile daily threshold value across the summer for each station. (MS Office)

Figure 3

Heatwave identification for Amman station for June-October 2002. (MS Office)

Figure 4

Amman's Station Heatwave's characteristics Temporal Development (1971 – 2005). DY refers to number of heatwave days per year. HF refers to the number of heatwaves per year. HMAI refers to the average intensity of the most intense heat wave for each year. (MS Office)

Figure 5

Heatwave's characteristics yearly change for the 13 stations in Jordan. Yearly change in DY graph represent the average yearly change in number of heatwave days through the study duration for all stations. Yearly change in HF represents the average yearly change in number of heatwaves for the study duration. Yearly change in HMAI refers to the yearly change in the average temperature of the most intense heatwave every year in Celsius. (MS Office)

Figure 6

Jordan's heatwave characteristics in 1970 vs 2005. The graphs represent the spatial distribution of calculated values for each station at the start point of the study (1970) and at the end of the study (2005). (ArcMap)

Figure 7

Spatiotemporal distribution of heatwave's characteristics in Jordan. The graphs represent spatial distribution of calculated trend line slopes of DY, HF, and HMAI to create a spatiotemporal representation. (ArcMap)