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Observed changes in the characteristics of heat waves in hot and dry regions of Iran

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Abstract— Research on heat waves is greatly important not only due to their effect on social, economic, and ecological systems, but also due to the complexity of the processes that create them. Therefore, this research mainly investigated the trend of long-term changes in various characteristics of heat waves in hot and dry regions of Iran. For this purpose, the daily maximum temperature data of 15 meteorological stations in the central and southeastern parts of Iran were used from 1985 to 2018. Using the excess heat factor (*EHF*) index, five different features of heat waves including the number of heat waves (HWN), heat waves duration (HWD), heat waves frequency (HWF), heat waves mean (HWM), and heat waves magnitude (HWA) were extracted for all the studied stations. Then, their trend of long-term changes was analyzed using the Sen's slope estimator nonparametric method. The results showed that on a regional scale, all five characteristics of heat waves have an increasing trend at a significance level of 95%, so an increase of 0.5 events per decade has been observed for the HWN. The trend of long-term changes in the HWD has also indicated an increase of 0.91 days per decade. The HWF has shown more drastic changes than other characteristics of heat waves, so in every decade 2.61 days have been added to the frequency of days contributing to the occurrence of heat waves. The regional intensity of HWM and HWA also show an increase of 0.1 and 0.4 °C in each decade, respectively. These findings show the importance of choosing a suitable index for monitoring different characteristics of heat waves. The *EHF* index is a suitable index, which can be one of the efficient indices in this regard.

Key-words: climate change, trend, Sen's slope estimator, heat waves, Iran

1. Introduction

It is important to research extreme climate events due to their effect on social, economic, and ecological systems and the complexity of the processes that create them. Investigating extreme climate events always requires considering different spatial and temporal scales, different modes of variability, and thermodynamic processes that create them (*Stocker et al.*, 2013). Researches show that scientific knowledge about some atmospheric processes has made substantial progress and has provided a platform for designing climate models and forecasting numerical weather models (*Tavosi et al.,* 2010).

According to the Special Report of Extreme Events (SREX) prepared by Working Groups I (WGI) and II (WGII) of the Intergovernmental Panel on Climate Change (IPCC), weather and climate extremes are rare events that occur in a certain period by passing a certain threshold value. The threshold value can vary from place to place (*Field*, 2012). In this definition, the two terms of weather and climate extremes are mentioned. Extreme weather events are events that occur in a short period, for example, from a few hours to several weeks, while extreme climate events are a set of events that occur in a longer period, for example, during a season (*Stocker et al.,* 2013).

The American Meteorological Society defines a heat wave simply as "a period of abnormally and uncomfortably hot and usually humid weather" (AMS, 2000). Many efforts have been made to add more details to this definition. Unfortunately, due to the lack of a common set of parameters, it has become more complicated (*Choi* and *Meentemeyer,* 2002; *Robinson*, 2001). The excess heat factor (*EHF*) (*Nairn et al.,* 2009) is one of the important indicators for studying the effects of heat waves on human health, especially in mid-latitude climates (*Scalley et al.,* 2015; *Hatvani-Kovacs et al*., 2016; *Jegasothy et al.,* 2017; *Nairn et al.,* 2018; *Oliveira et al.,* 2022). *Nairn* and *Fawcett* (2013) have introduced this index as a simpler and more efficient index compared to other bioclimatic indices such as universal thermal climate index (UTCI) (*Zare et al*., 2018) and physiological equivalent temperature (PET) (*Höppe*, 1999). The Expert Team of Sector-Specific Climatic Indicators (ET-SCI) affiliated with the World Meteorological Organization (WMO) has introduced 64 precipitation and temperature extreme indices to improve decision-making for planning, organization, risk management, and adaptation to climatic variability and change. Out of these 64 precipitation and temperature extreme indices, about 47 of them were related to temperature extreme indices. The *EHF* index is one of the main indicators of detecting heat waves that have been used by this team. Based on this index, five different characteristics of heat waves such as the number of heat waves (HWN), heat waves duration (HWD), heat waves frequency (HWF), heat waves mean (HWM), and heat waves magnitude (HWA) can be extracted (*Perkins* and *Alexander*, 2013).

According to the report of the Intergovernmental Panel on Climate Change (IPCC) in 2013, "it is very likely that the number of cold days and nights will decrease and the number of warm days and nights will increase on a global scale". In addition, “the heat waves frequency is likely to increase in large parts of Europe, Asia, and Australia" (IPCC, 2013). Various studies have also confirmed increasing trends in indicators related to heat waves in different parts of the world (*Li et al*., 2022; *Perkins-Kirkpatrick* and *Lewis*, 2020; *Rousi et al.,* 2022; *Yin et al.,* 2022). In Iran, many studies have focused on the changes in average minimum and maximum monthly, seasonal, and annual temperatures in different spatial scales (*Alijani et al.,* 2015; *Halabian et al.,* 2017; *Jahanbaksh et al*., 2018; *Khoshakhlagh et al*., 2011; *Montazeri,* 2014). The total results of these studies show that the changes in the average minimum temperatures were almost twice the changes in the average maximum temperatures (*Alijani et al*., 2012a). In this regard, in the average national scale of Iran, an increase of 0.2 °C per decade for the average annual maximum temperature and an increase of 0.4 °C per decade for the average annual minimum temperature have been reported (*Mahmoudi et al*., 2019). In addition, the results of regional scale studies in Iran are also increasing the annual average minimum temperature in a decade for Tehran to 0.68 °C (*Bidokhti* and *Ranjbar*, 2003), confirming the increase of 2 °C in Iran's day and night temperature in a hundred years (*Masoudian*, 2004) and predicting an increase of 2.75 °C for Northeast Iran (*Alizadeh* and *Kamali*, 2002).

This increase in average maximum and minimum temperatures can naturally intensify heat waves in Iran. *Darand* (2014) revealed three indices based on the 90th, 95th, and 99th percentiles of maximum temperatures and the intensity, duration, and frequency of Iran's heat waves to identify heat waves and analyze their trends in Iran. Then, the significance of the trends of these three indices was analyzed using the Mann-Kendall nonparametric test and their trend slope using linear regression. The findings of this research showed that the frequency, duration, and intensity of heat waves are increasing on low and flat lands such as Dasht-e Lut (northeast of Kerman province), plain lands of northeast Hormozgan province, Dasht-e Kavir and Khuzestan province and are decreasing on the heights of the Zagros and Alborz mountain ranges and other scattered heights. *Namroodi et al.* (2021) also reported an increasing trend in the number of heat wave in Iran. In that study, they showed that about 85% of the studied stations in Iran had an increasing trend in the heat wave number. *Esmailnejad et al.* (2014) also confirmed the same increasing trend in the heat wave number in Iran.

The central and southeastern parts of Iran are one of the most vulnerable areas of Iran to climate change due to their dry climate (*Alijani et al.,* 2015; *Mahmoudi et al.,* 2011). The increasing trend of temperature (*Sari Sarraf et al*., 2018) and the decreasing trend of precipitation (*Mahmoudi* and *Rigi Chahi*, 2019) in the last few decades have aggravated this vulnerability. Intensifying the various characteristics of heat waves is one of the climate hazards that can harm the fragile economic, social, environmental, health, and even political structure of this part of Iran. As mentioned above, various research have studied the changes in the characteristics of heat waves in Ira,n but there are still many study gaps for the central and southeastern parts of Iran. In these studies, the central and southeastern parts of Iran have not been considered independent geographical units. The heat wave indices used in these studies are mostly based on percentile thresholds and mostly focused on the heat waves frequency. Therefore, this study mainly aims to fill these study gaps for this part of Iran. Therefore, the *EHF* will be used for the first time to extract five different characteristics of heat waves in Iran. The trend of long-term changes in these five different characteristics of heat waves will also be analyzed for the cental and southeastern parts of Iran.

2. The study area

The area studied in this research includes the five provinces of Sistan and Baluchestan, Kerman, South Khorasan, Yazd, and Hormozgan, which cover an area of about 659,378 square kilometers, equal to 40% of Iran's area, in the center, south, and east of it (*Fig. 1a*). According to the 2016 census, these five provinces had a population of 9,623,578 people, equal to 12% of the total population of Iran (Statistical Center of Iran, 2016).

According to De Martonne's climate classification (*De Martonne*, 1909), the entire studied area has a dry climate (*Table 1*). The average annual rainfall in this area is nearly 109 mm, and its spatial distribution is very different in different parts, so the average annual rainfall in Bandar Abbas station is 171.1 mm, and in Zabol station is 52.6 mm (*Fig. 1b*). The average annual temperature of this area is 22.2 degrees Celsius. The lowest average annual temperature belongs to Birjand station at 16.5 °C and the highest one at 27.8 °C belongs to Bandar-e Lengeh station (*Fig. 1c*).

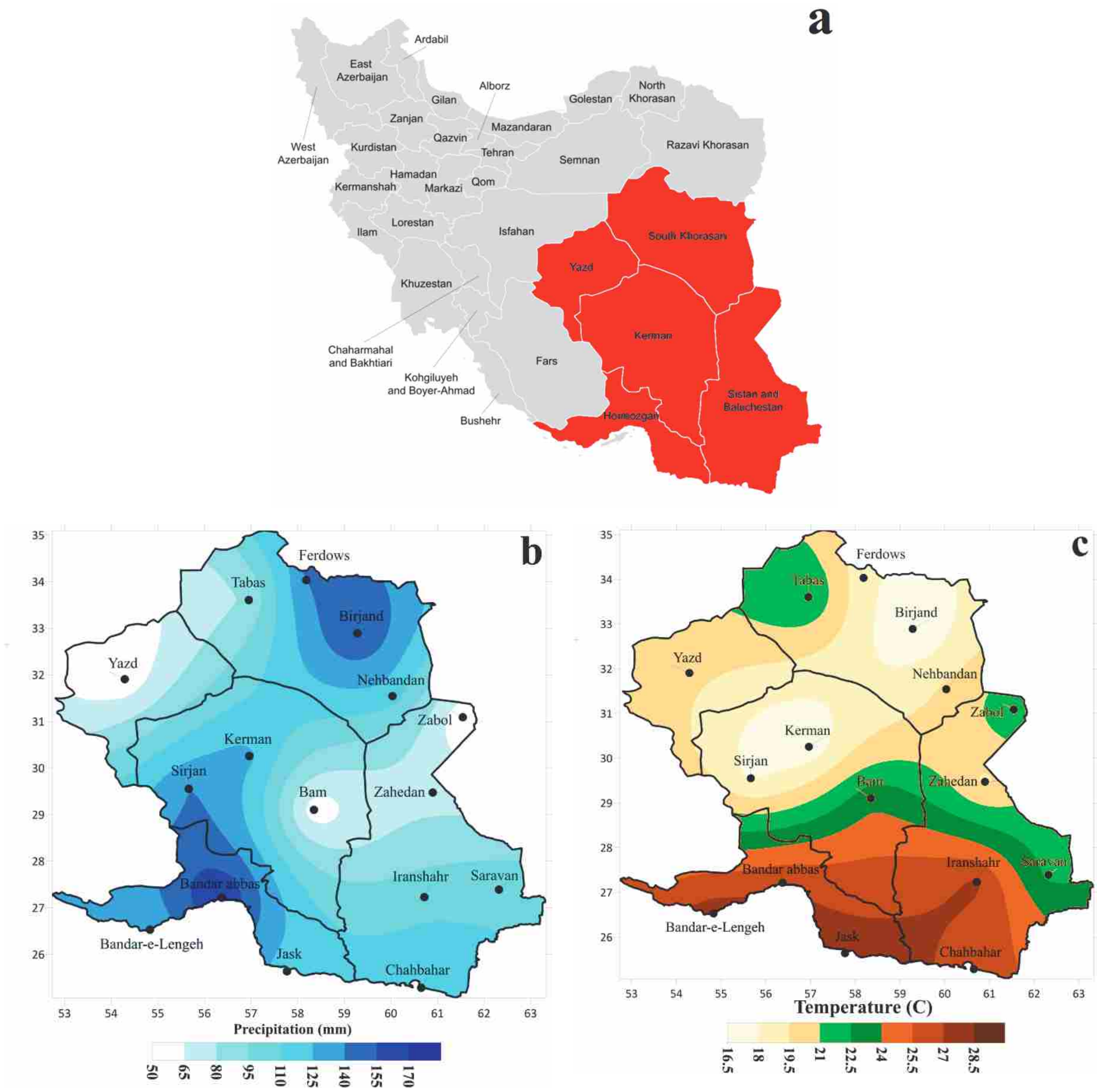

Fig. 1. (a) Geographical location of the cental and southeastern parts of Iran and its administrative divisions. (b) Spatial distribution of the long-term average annual precipitation in the cental and southeastern parts of Iran (1985–2018). (c) Spatial distribution of the long-term average annual temperature in the center and south Eastern Iran (1985–2018).

3. Data

In this research, the trend of long-term changes in the *EHF* was used as an index proposed by the World Meteorological Organization (WMO) to extract different characteristics of heat waves in the cental and southeastern parts of Iran. The daily maximum temperature data of 15 Iranian meteorological stations for a period of 34 years (1985–2018) were received from the Iran Meteorological Organization.

The geographic location of the studied stations is shown in *Fig. 2* and their geographic characteristics are given in *Table 1*. These stations have the most complete and reliable data in the cental and southeastern parts of Iran. The few statistical gaps in this station were reconstructed using the Pearson's correlation coefficient and the linear regression method. Quality control of data and their homogeneity tests were carried out using the runs test method and the homogeneity of all data was confirmed at a probability level of 95%.

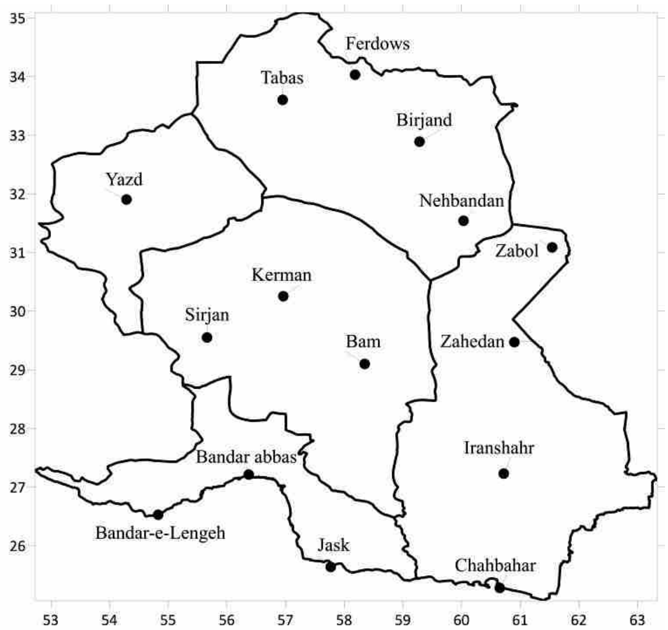

Fig. 2. The name and geographical location of the studied stations in the cental and southeastern parts Iran

Table 1. Geographical characteristics of the studied stations in the cental and southeastern parts of Iran

Station	longitude	latitude	altitude (m)	climate
Zahedan	60° 53′	29° 28′	1370	dry
Bam	58° 21′	29° 06′	1067	dry
Bandar abbas	56° 22′	27° 13′	10	dry
Bandar-e-Lengeh	54° 50′	26° 35′	14	dry
Birjand	59° 12′	32° 52′	1491	dry
Chabahar	60° 37′	25° 17′	8	dry
Ferdows	58° 10′	34° 01′	1293	dry
Iranshar	60° 42′	27° 12′	591	dry
Jask	57° 46′	25° 38′	5.2	dry
Kerman	56° 58′	35° 15′	1754	dry
Minab	57° 05′	27° 06′	30	dry
Sirjan	55° 41′	29° 28′	1739	dry
Tabas	56° 55′	33° 36′	711	dry
Yazd	54° 17′	31° 54′	1237	dry
Zabol	61° 29′	31° 02′	489	dry

4. Methodology

4.1. Excess heat index (EHF)

The calculation of *EHF* is the result of multiplying two sub-indexes of excess heat: (1) the significance excess heat index (EHF_{sig}), which measures the difference between the average maximum temperature of 3 days with the 95th percentile of the average maximum temperature of the reference period (1985–2018) and (2) the acclimatization excess heat index (EHF_{accl}), which measures the difference between the average maximum temperature of three days and the average maximum temperature of the last 30 days. The first sub-index shows excess heat as a long-term anomaly (climate scale), and the second sub-index considers the heat stress amount as a short-term anomaly. The second sub-index is based on the logic that biological systems are less able to adapt to sudden increases in temperature (*Nairn* and *Fawcett*, 2013). These two sub-indexes and the *EHF* are calculated according The following equations (*Alexander* and *Herold*, 2016; *Nairn* and *Fawcett*, 2013).

$$EHF_{sig} = \frac{(T_i + T_{i+1} + T_{i+2})}{3} - T_{95}, \tag{1}$$

$$EHI_{accl} = \frac{(T_i + T_{i+1} + T_{i+2})}{3} - \frac{(T_{i-1} + \dots + T_{i-30})}{30}, \tag{2}$$

$$EHF = EHF_{sig} \times max(1, EHI_{accl}), \tag{3}$$

where T is the average maximum daily temperature and T_{95} is the 95th percentile of the average maximum temperature of the reference period (1985–2018). It should be noticed that the calculation basis of this index is based on the average daily air temperature (the average between the daily maximum and minimum temperatures). This study used the daily maximum temperature instead of the average daily air temperature.

When the *EHF* result is detected as positive, its value will be a quadratic measure of heat wave intensity that responds to both short-term and long-term anomalies. The measurement unit of this index is $°\mathrm{C}_\mathrm{L}^2$, where L refers to the local nature of the threshold and the *EHF* results. The *EHF* extracted the five different characteristics of heat waves including the HWN, HWD, HWF, HWM, and HWA. *Table 2* shows the definitions and measurement units of these five indicators.

Table 2. Aspects of heat wave analyzed based on *EHF* with their names, definitions, and units

Identifier	Heatwave aspect	Definition	Unit
HWN	Heat waves number	The annual number of summer heat waves that have the conditions of continuity for at least 3 consecutive days with positive *EHF* values.	Number of events
HWD	Heat waves duration	In terms of time, the longest heat wave of the summer season has the conditions of continuity for at least 3 consecutive days with positive *EHF* values.	Days
HWF	Heat waves frequency	The total number of days in the summer season that was involved in a heat wave and had the conditions of continuity for at least 3 consecutive days with positive *EHF* values.	Days
HWA	Heat waves magnitude	The hottest day of the hottest summer heat wave has continued for at least 3 consecutive days with positive *EHF* values.	$°C^2$
HWM	Heat waves average	The average magnitude of all summer heat wave days that have the conditions of continuity for at least 3 consecutive days with positive *EHF* values.	$°C^2$

It should be noted that two features of heat wave intensity such as HWA and HWM depend on the local temperature range changes, which are also different according to geographical latitude. Therefore, the annual values and the amount of change in HWA and HWM in different regions can only be compared with each other through the normalization of local heat wave intensity. To overcome this limitation, severity methodology based on *EHF* (EHF_{severity}) was incorporated by *Nairn et al.* (2018) to determine how severe a heat wave day is compared to the local climatology. Based on the normalization of the *EHF* daily intensity value by the 85th percentile (*EHF*85p) of a climatological period, the dimensionless index *EHF* severity is calculated based on Eq.(4), which is based on the extreme value theory. Here, *EHF* daily intensities are normalized by the 85th percentile for the climatological period 1985–2018:

$$EHF_{severity} = EHF \div EHF_{85p}. \quad (4)$$

In the analysis section of this study, instead of the normalized values of two characteristics of HWA and HWM (in °C$^{2)}$, their temperature equivalent (in °C) was used. It seems that using temperature equivalent instead of normalized values can provide a better understanding of the magnitude and intensity of heat waves in this region of Iran. All calculation steps of this index are programmed in MATLAB software environment.

4.2. The Sen's slope estimator nonparametric method

The Sen's slope estimator nonparametric test was used to analyze the trend of long-term changes in various characteristics of heat waves in the cental and southeastern parts of Iran. This method was first presented by *Theil* in 1950, and then developed and expanded by *Sen* in 1968. Like many other non-parametric methods such as Mann-Kendall, this method is based on analyzing the difference between the observations of a time series. This method can be used when the trend in the time series is a linear trend. This means that $f(t)$ can be expressed as:

$$f(t) = Qt + B \;, \tag{5}$$

where Q is the trend line slope and B is the constant coefficient value.

The slope between each pair of observational data must be first calculated using the following equation to calculate the trend line slope, i.e., Q:

$$Q_i = \frac{x_j - x_k}{j-k} \;, \tag{6}$$

where $j > k$. In this equation, x_j and x_k are observational data at times j and k, respectively. A slope is obtained for each pair of observational data by applying this relationship. In addition, a time series of calculated slopes is obtained by placing these slopes next to each other. That is, if there is an n number x_j in the time series (in this research, n=34), we will have an estimate of the slope (Q_i) equal to $N = n(n-1)/2$.

In the next step, the median of the studied time series should be obtained. For this purpose, N number of Q_i are sorted from small to large. Then, the median of the time series is determined using one of the following equations. If the number of observations of the studied time series is odd, Eq.(7) is used, and if it is even, Eq.(8) is used:

$$Q = Q_{[(N+1)/2]} \;, \tag{7}$$

$$Q = \frac{1}{2} = \left[Q_{N/2} + Q_{[(N+2)/2]}\right] . \tag{8}$$

The result of these equations is to obtain the trend line slope (Q_{med}). If the trend line slope is positive, it indicates an upward trend, and if it is negative, it indicates a downward trend.

The next step is to test the obtained slope in the confidence interval of α= 0.05. The following equatuion is used to perform this test:

$$C_a = Z_{1-\alpha/2}\sqrt{VAR(S)} \;, \tag{9}$$

where Z is the statistic of the standard normal distribution in a two-way test which is equal to $Z = 1.96$ for 95% confidence level, and $VAR(S)$ is the variance of the parameter S. The following steps must be followed to obtain the value of the parameter:

a) Calculating the difference between each sentence in a series and applying the sign function (sgn) and extracting the parameter *S*:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \ , \tag{10}$$

where n is the number of serial observations (in this research it is 34 years), and x_j و x_k are the data of the jth and kth series, respectively.

b) Calculating the sign function (sgn) which can be calculated as follows:

$$sgn(x) = \begin{cases} +1 if(xj - xk) > 0 \\ 0 if(xj - xk) \ = 0 \\ -1 if(xj - xk) < 0 \end{cases} \ . \tag{11}$$

c) Calculating the variance *S* using one of the following relationships. If the number of time series data is greater than ten, Eq.(12) is used, and if it is less than nine, Eq.(13) is used:

$$VAR(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t(t-1)(2t+5)}{18} \ , \tag{12}$$

$$VAR(S) = \frac{n(n-1)(2n+5)}{18} \ , \tag{13}$$

where, *n* is the number of observational data, *m* is the number of series in which there is at least one repeated data, and *t* represents the frequency of data with the same value.

Finally, the upper and lower confidence limits are calculated through the following relationships:

$$\begin{cases} M_1 = \frac{n' + C_a}{2} \\ M_2 = \frac{n' - C_a}{2} \end{cases} \ , \tag{14}$$

where n' is the number of slopes obtained by the method of Eq.(8).

Now, the M_1th and M_{2+1}th slopes from among the calculated slopes are extracted. If the number zero is in the range between the two slopes extracted above, the null hypothesis is accepted, and the absence of a trend in the data series is confirmed. Otherwise, the null hypothesis is rejected, and the existence of a trend in the confidence level of the test is accepted.

Finally, n number of differences $x_i - Qt_i$ is calculated to obtain the value of B in Eq.(5). Then, the median of these values provides the estimate of B (*Alijani et al.*, 2012b).

5. Analysis and discussion

5.1. Heat waves climatology

For all the studied stations in the cental and southeastern parts of Iran, the different characteristics of heat waves including HWN, HWD, HWF, HWM, and HWA were extracted using the *EHF* index. The climatological mean (1985–2018) of each of these characteristics was calculated for the cental and southeastern parts of Iran (the long-term average of the numerical values of each of the characteristics of heat waves for all stations were added together and divided by the number of stations), and their results are given in *Table 3*.

Table 3. Climatic average (1996–2018) of different characteristics of heat waves for the cental and southeastern parts of Iran

Different characteristics of heat waves	**Annual average**
Heat waves number	2.5
Heat waves duration	8.0
Heat waves frequency	14.6
Heat waves mean	41.2
Heat waves magnitude	43.4

The climatic average of HWN for the cental and southeastern parts of Iran was 2.5 events per year (*Table 3*). Minab station with 2.9 and Sirjan station with 1.2 occurrences per year have the highest and lowest station average values of this feature of heat wave, respectively (*Fig. 3a*). The spatial distribution map of this feature of the heat wave in the cental and southeastern parts of Iran shows that its lowest values are observed in the western and the highest in the southern (northern coasts of the Oman Sea and the Persian Gulf) parts of the study area (*Fig. 3a*). In terms of the duration, the climatic average of the HWD in this part of Iran was equal to 8 days (*Table 3*). The southern part of the studied area has the lowest and the western part has the longest heat wave duration (*Fig. 3b*). Jask station with 5.5 days and Sirjan station with 11.5 days had the longest and shortest heat waves duration on a station scale, respectively (*Fig. 3b*). The HWF (the number of days involved in the occurrence of a heat wave) was the third feature of heat waves, whose climatic mean was analyzed for the cental and southeastern parts of Iran. The climatic average of this index for this part of Iran was 14.6 days (*Table 3*). Its spatial distribution in the cental and southeastern parts of Iran indicated the existence of low values in the southern half and high values in the western and central parts of the studied region (*Fig. 3c*). Jask station with 11.1 days and Sirjan station with 18 days have the lowest and highest heat waves frequency, respectively, in a station scale (*Fig. 3c*). The climatic average of HWM (average temperature of all heat waves) for the cental and southeastern parts of Iran was equal to 41.2 °C (*Fig. 3*). The highest values of this feature were observed in the northwest, east, center of Sistan and Baluchistan province, and south of Kerman province, and the lowest values were observed in the southeastern part of the study area (*Fig. 3d*). Iranshahr station with 44.2 °C and Chabahar station with 35.2 °C had the highest and lowest values of this heat waves characteristic, respectively (*Fig. 3d*). Finally, the average calculated for the heat waves magnitude was equal to 43.4 °C (*Table 3*). The spatial pattern of this feature is almost similar to the intensity feature of heat waves. The highest value of this feature was observed in the northwestern, eastern, and central parts of Sistan and Baluchistan province and south of Kerman province, and the lowest value was observed in the southeast ern part of the study area (*Fig. 3e*). Chabahar station with 38.6 and Minab station with 48.2 °C have the highest and lowest values of this feature in the cental and southeastern parts of Iran, respectively (*Fig. 3e*).

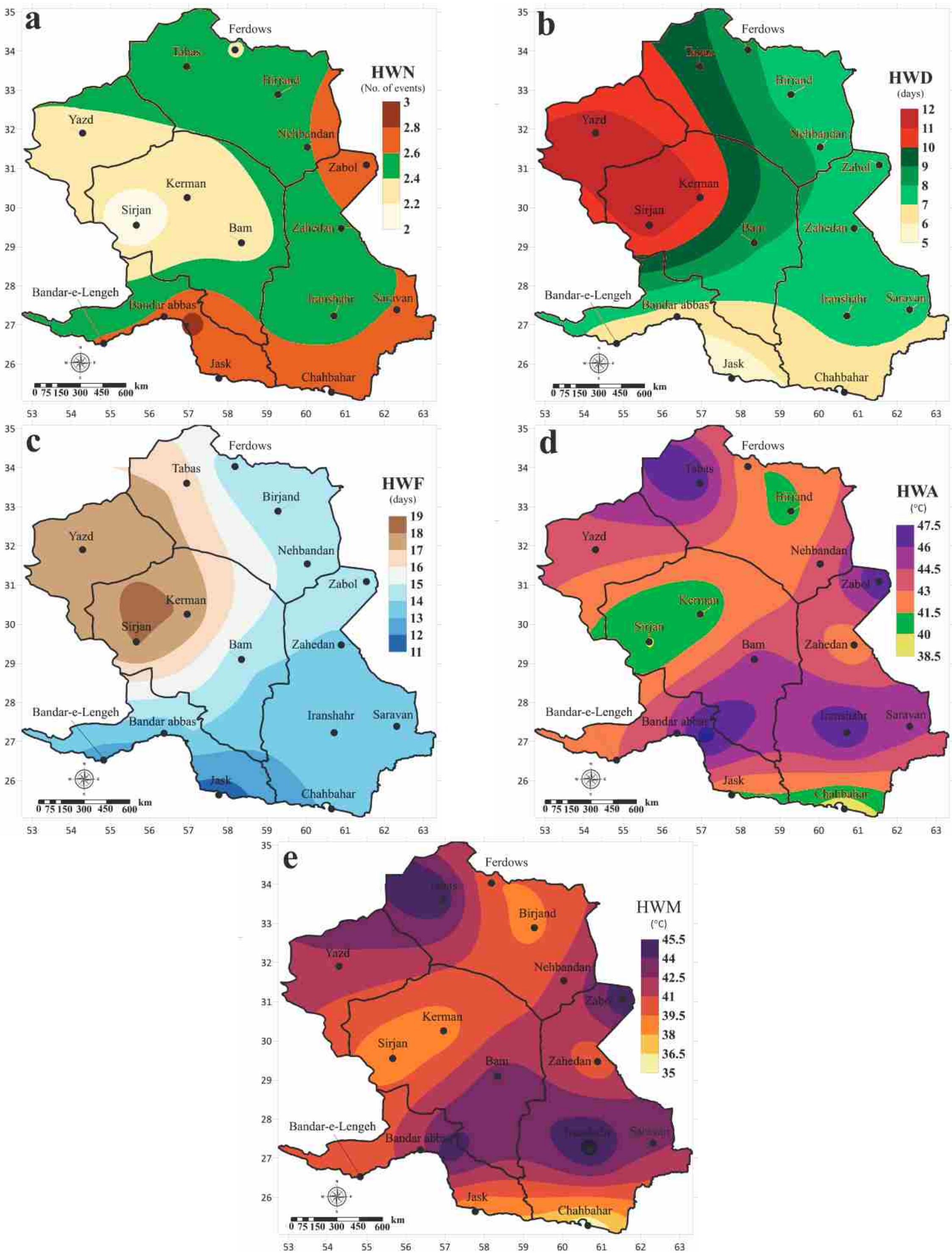

Fig. 3. Different characteristics of heat waves in the cental and southeastern parts of Iran including (a) HWN, (b) HWD, (c) HWF, (d) HWM, and (e) HWA using the *EHF* index in 1986–2018.

The distribution of the total frequency of heat waves in different months of the year was also considered. As it is presented in *Table 4*, the highest frequency of heat waves in the studied stations in the cental and southeastern parts of Iran was concentrated in July, June, and August, respectively. In these three months, all the studied stations have experienced the maximum number of heat waves. Among the studied stations, Chabahar station was the only station that experienced heat waves in April and October. On April 1 and September 6, heat waves occurred at this station during the 34 years studied (1985–2018).

Table 4. Distribution of the total frequency of heat waves in the 7 months of the warm period of the years 1985–2018

Station	April	May	June	July	August	September	October
Zahedan	0	3	30	39	8	0	0
Bam	0	2	33	30	6	0	0
Bandar abbas	0	11	26	21	16	7	0
Bandar Lengeh	0	5	14	23	18	3	0
Birjand	0	2	29	39	11	0	0
Chabahar	1	31	36	10	2	2	6
Ferdows	0	0	28	34	12	2	0
Iranshar	0	3	43	31	5	1	0
Jask	0	14	40	17	9	0	0
Kerman	0	1	28	35	8	0	0
Minab	0	15	31	19	17	7	0
Sirjan	0	0	20	38	9	0	0
Tabas	0	0	25	40	15	0	0
Yazd	0	0	21	36	15	0	0
Zabol	0	3	24	35	12	1	0

5.2. Analysis of the trend of long-term changes in different characteristics of heat waves

This section presents the results of the trend analysis of long-term changes in five characteristics of heat waves in the cental and southeastern parts of Iran. The

HWN was the first feature of the heat waves that was noticed in the cental and southeastern parts of Iran. This feature of the heat waves is obtained by counting the number of heat waves that occur each year. The trend of long-term changes in the HWN on a regional scale for the cental and southeastern parts of Iran shows a significant increasing trend at the 95% probability level (*Table 5*). Based on this increasing trend, it is observed that 0.5 cases have been added to the heat waves number in the cental and southeastern parts of Iran in each decade (*Table 5*). In addition, the results of trend analysis at a station scale show an increasing trend for all studied stations except Sirjan station in Kerman province. Among the stations with an increasing trend, the two stations of Bandar-e Lengeh and Zabul have the highest values of the increasing trend in the heat waves number with an increasing trend of 1.04 and 0.93 in each decade, respectively (*Fig. 4a*). In terms of spatialdistribution, the highest change trend slope has been generally observed in the western half of Hormozgan province, southern part of Kerman province, central, and northern parts of Sistan and Baluchistan province (*Fig. 4a*). It should be noted that the trends of these changes were not significant for all the studied stations at the 95% probability level, and only Bandar Abbas, Iranshahr, Gorgan, Minab, Bam, Yazd, Bandar-e Lengeh, Zabul, and Zahedan stations were significant, the locations of which are shown in *Fig. 4b*. In line with the results of this part of the study, *Namroodi et al.* (2021) reported an increasing trend in the heat wave number in Iran. In that study, they showed that about 85% of the studied stations in Iran had an increasing trend in the heat wave number. In addition, *Esmailnejad et al.* (2014) confirmed the same increasing trend in the heat wave number for Iran. It should be noted that the indicators used in these two studies to identify Iran's heat waves were very different from the present study.

Table 5. The average trend slope of the change of different characteristics of heat waves in a decade for the regional scale of the cental and southeastern parts of Iran

Different characteristics of heat waves	**The average slope trend changes in a decade**
Heat waves number	0.52
Heat waves duration	0.91
Heat waves frequency	2.61
Heat waves mean	0.1
Heat waves amplitude	0.4

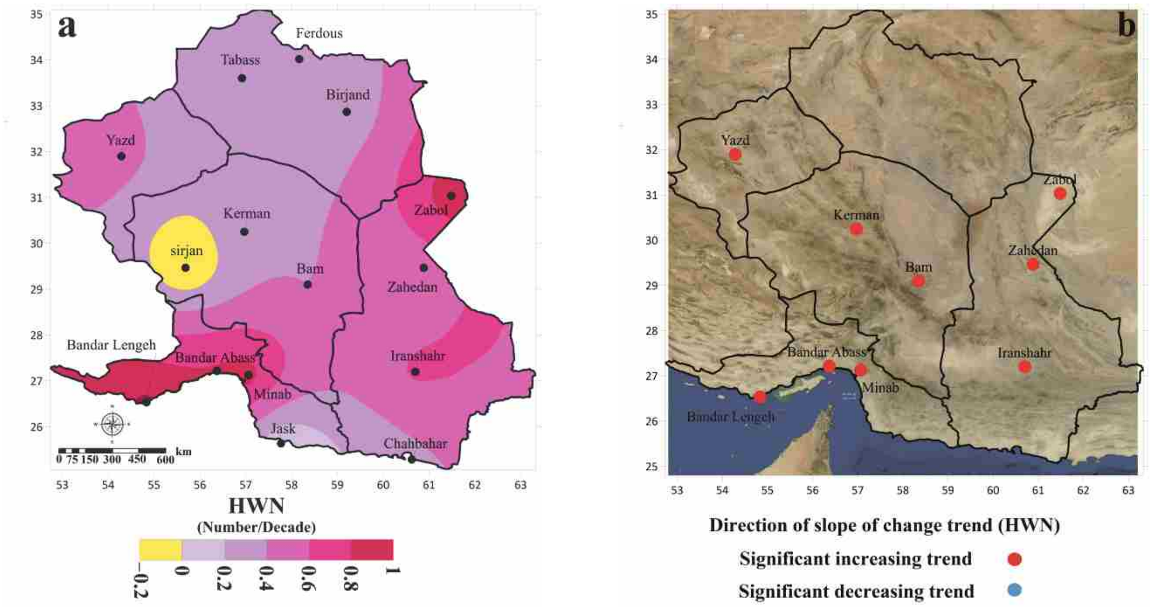

Fig. 4. (a) Spatial distribution of trend slope values of HWN changes in the cental and southeastern parts of Iran in terms of number per decade (1985–2018), and (b) the name and geographical location of the stations with significant trends at the probability level of 95% for the HWN in the cental and southeastern parts of Iran in terms of number per decade.

Another feature of heat waves is the heat wave duration, which is indicated by the abbreviation HWD. In this feature, the longest heat wave of each year is defined as the heat wave duration. A significant increasing trend is observed in this feature of the heat wave in the regional average of the cental and southeastern parts of Iran. Based on this increasing trend, 0.91 days will be added to the heat wave duration in the cental and southeastern parts of Iran every decade (*Table 5*). At the station scale, except for the Jask station, whose long-term change trend has been decreasing, the rest of the studied stations have had an increasing trend (*Fig. 5a*). All these trends, both decreasing and increasing ones, were not significant at the 95% probability level. Stations of Zabul (2.23 days per decade), Kerman (2.06 days per decade), Iranshahr (1.46 days per decade), Bam (1.33 days per decade), Tabas (1.3 days per decade), Bandar-e Lengeh (1.15 days per decade), and Chabahar (1.03 days per decade) were the seven stations whose changes were significant at the 95% probability level. The spatial distribution of these seven stations is shown in *Fig. 5b*. In addition, the spatial distribution map of trend slope values of this feature of the heat wave changes in the cental and southeastern parts of Iran does not show a specific spatial pattern, but the northern part of Sistan and Baluchistan province and the northern part of Kerman province can be named as two important centers of increasing changes, while the west coast of the Oman Sea is the most important center of decreasing changes (*Fig. 5a*).

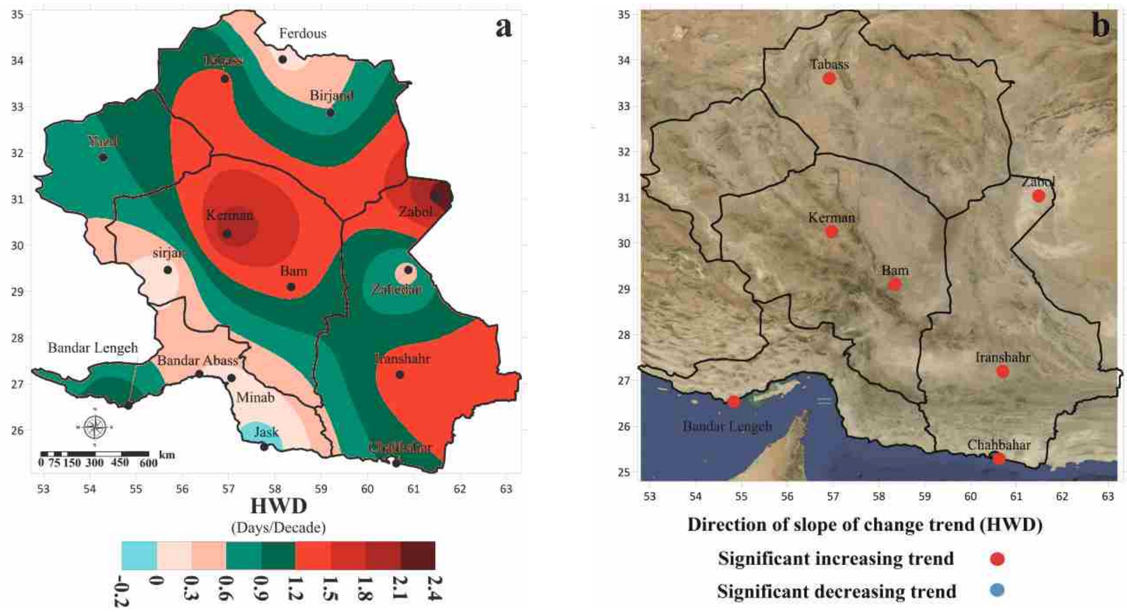

Fig. 5. (a) S Spatial distribution of trend slope values of HWD changes in the cental and southeastern parts of Iran in terms of day in the decade (1985–2018) and (b) the name and geographical location of the stations at the probability level of 95% probabilities for the duration of heat waves (HWD) in the cental and southeastern parts of Iran in terms of day in the decade

The HWF is the third feature of the heat waves whose long-term changes trend in the cental and southeastern parts of Iran were considered. HWF refers to the total number of days involved in the occurrence of various heat wave events in a year. The trend analysis of this feature of the heat waves on a regional scale for the cental and southeastern parts of Iran shows an increasing trend of 2.61 days per decade. This increasing trend has been significant at the 95% probability level (*Table 5*). The trends analysis at the station scale also shows that out of 15 stations studied, 13 stations have an increasing trend and 2 stations have a decreasing trend. The two stations, Ferdous and Jask, whose long-term changes trend has been decreasing, are not significant at the 95% probability level. Among the 13 stations with an increasing trend, the increasing trends of 11 stations have been significant at the probability level of 95%. In *Fig. 6b*, the geographical location of these stations is shown on a map of the cental and southeastern parts of Iran. The most observed changes among the studied stations belong to the stations of Zabul (5.23 days per decade), Bandar-e Lengeh (5.09 days per decade), Minab (4.52 days per decade), and Iranshahr (4.35 days per decade). *Fig. 6a* shows the spatial distribution of the slope values of the trend of the long-term change in HWF for the study area. According to this map, no specific spatial pattern of changes can be observed in the cental and southeastern parts of Iran, but two centers of decreasing changes can be observed in the southern and northern parts of the studied area, and several centers of increasing changes in the central and western parts of Hormozgan province, in the northern and central parts of Sistan and Baluchistan province (*Fig. 6a*).

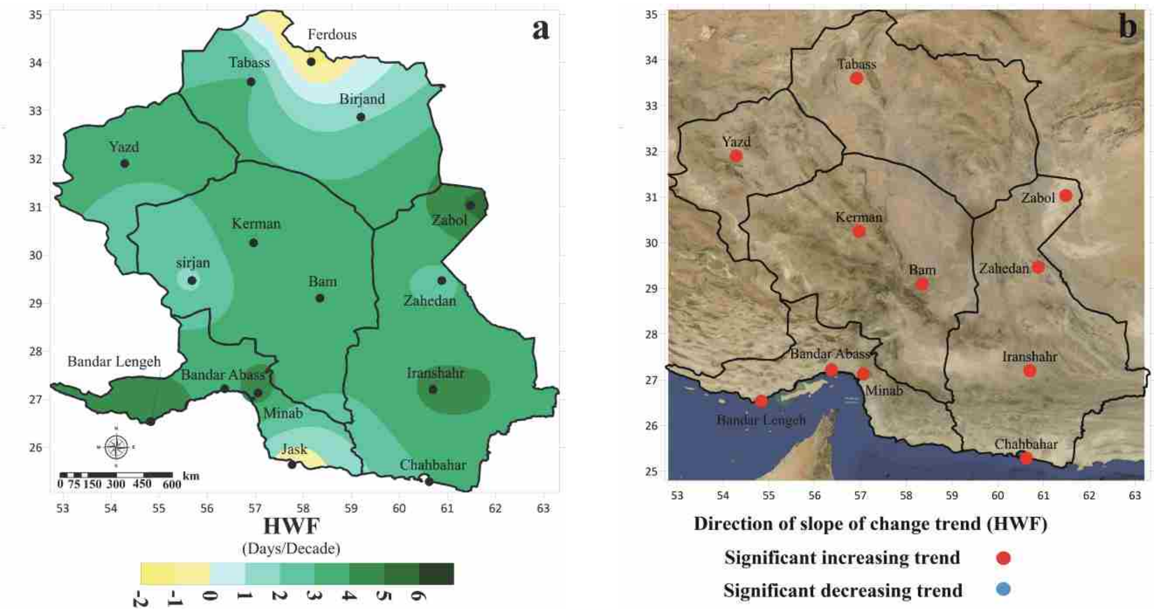

Fig. 6. (a) Spatial distribution of trend slope values of HWF changes in the cental and southeastern parts of Iran in terms of day in the decade (1985–2018), and (b) the name and geographic location of the stations with significant trends at the probability level of 95% for the heat waves frequency (HWF) in the cental and southeastern parts of Iran in terms of days per decade.

The long-term changes trend of HWM (average temperature of all heat wave events in one year) was analyzed both at a regional scale and at a station scale for the cental and southeastern parts of Iran. As mentioned, the regional average of this feature of the heat wave for the cental and southeastern parts of Iran was 41.2 °C (*Table 4*). At the regional scale, a significant increasing trend has been observed at the 95% probability level with a slope value of 0.1 °C in each decade. In other words, 0.1 °C is added every decade to the HWM in the cental and southeastern parts of Iran (*Table 5*). At the station scale, it was also observed that the trend of the long-term change in this feature of the heat wave was decreasing at the three stations of Sirjan, Bandar-e Lengeh, and Ferdous. The decreasing trend of these three stations also was not significant at the 95% probability level. Among the remaining 12 stations with increasing trends, 6 stations have confirmed their increasing trends at a probability level of 95%. *Fig. 7b* shows the location and geographical distribution of these 6 stations with a significant increasing trend. Stations of Bandar Abbas (0.15 °C per decade), Yazd (0.15 °C per decade), Zabul (0.15 °C per decade), Minab (0.12 °C per decade), Kerman (0.11 °C per decade) and Bam (0.11 °C per decade) had the highest values of the trend slope change among the studied stations. The spatial distribution map of trend slope values of this feature of the heat wave change was also drawn for the cental and southeastern parts of Iran (*Fig. 7a*). Based on this map, three main centers of increasing changes were observed in the northern part of Sistan and Baluchistan province, in the northern half of Yazd province, the central part of

Hormozgan province, and the cental part of Kerman province (*Fig. 7a*). The centers of decreasing changes can also be identified in the northern part of South Khorasan province, the western part of Kerman province, and the western part of Hormozgan province.

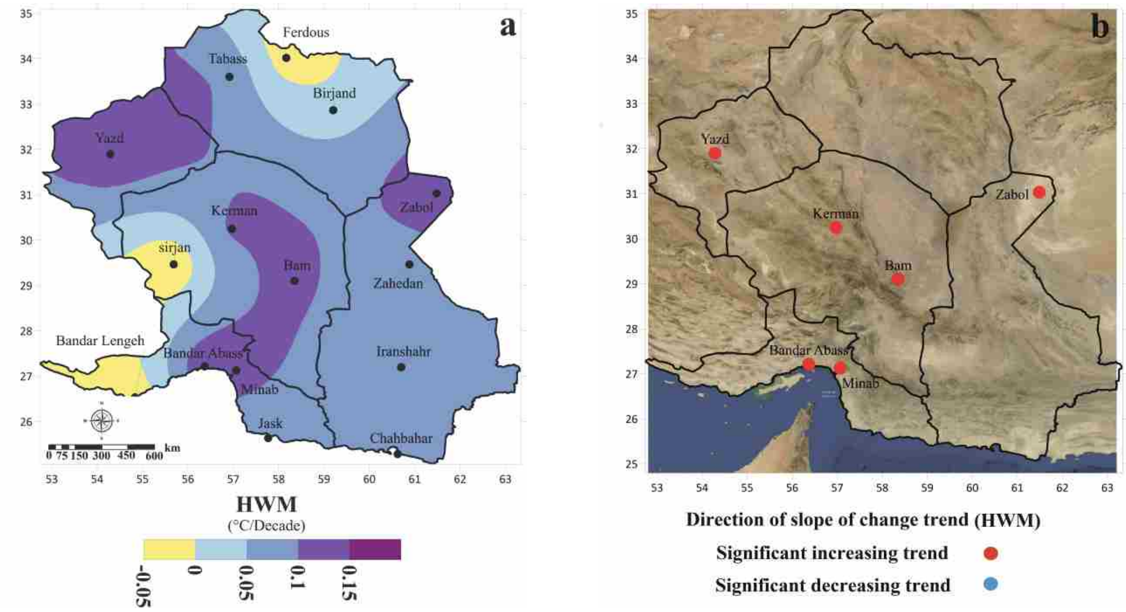

Fig. 7. (a) Spatial distribution of trend slope values of HWM changes in the cental and southeastern parts of Iran in terms of days per decade (1985–2018), and (b) the name and geographic location of the stations with significant trends at the probability level of 95% for the heat wave mean (HWM) in central and southeastern Iran in terms of days per decade.

HWA was the last feature of the heat wave whose long-term changes trend were analyzed. HWA is defined as the highest temperature and the hottest heat wave event in a year. Its regional average was previously calculated for the cental and southeastern parts of Iran, which is equal to 43.4 °C (*Table 4*). The trend analysis results of long-term changes in this feature of the heat waves on a regional scale show a trend slope of 0.4 °C in each decade for the cental and southeastern parts of Iran, which was also significant at the 95% probability level (*Table 5*). On a station scale, 14 stations have an increasing trend and one station has a decreasing trend. The stations of Bandar Abbas, Iranshahr, Kerman, Minab, Zahedan, and Zabul have significant trends for this characteristic of the heat waves at the probability level of 95% (*Fig. 8a*). Among all the studied stations, the highest trend slope change belongs to the three stations of Bandar Abbas (0.81 °C per decade), Minab (0.72 °C per decade), and Zabul (0.63 °C per decade). The spatial distribution of trend slope values of this feature of heat waves change indicates the existence of a specific spatial pattern in the cental and southeastern parts of Iran. In such a way, the trend slope changes are increasing from the northwest to the southeast. Two very distinct spatial centers of the increasing change trend can be observed in the central part of Hormozgan province (Bandar Abbas and Minab stations) and in the northern parts of Sistan and Baluchistan province (Zabul station) (*Fig. 8b*).

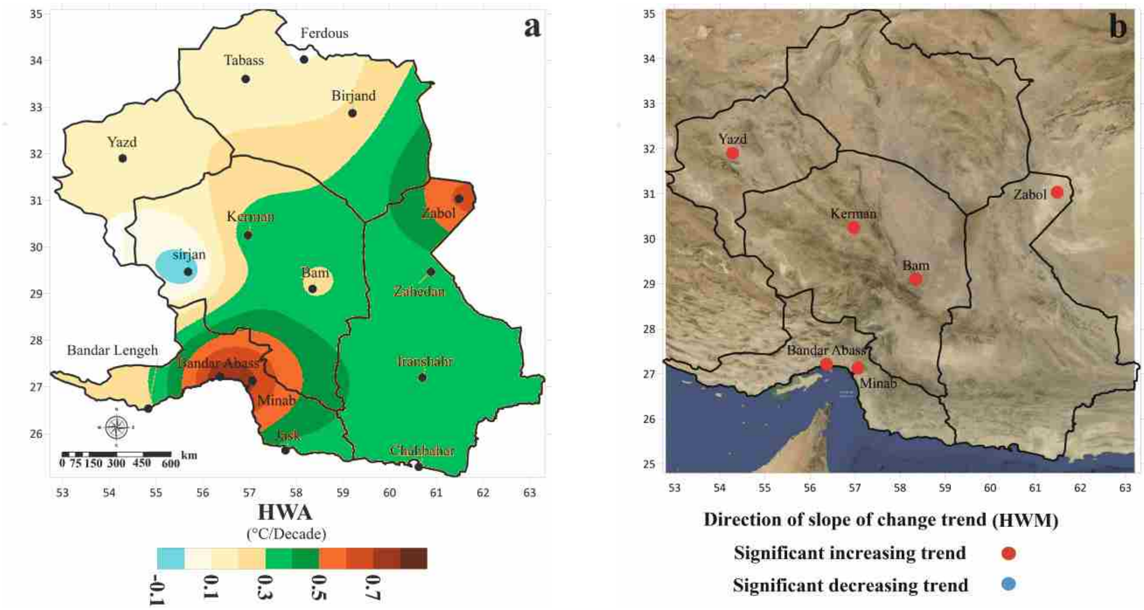

Fig. 8. (a) Spatial distribution of trend slope values of HWA changes in the cental and southeastern parts of Iran in terms of day per decade (1985–2018), and (b) the name and geographic location of the stations with significant trends at the probability level of 95% for HWA in central and southeastern Iran in terms of days per decade.

6. Conclusion

In this study, the climatology and long-term change trends of five different characteristics of heat waves in the cental and southeastern parts of Iran were analyzed using the EHF. The average of the highest number of heat wave events, and at the same time, the shortest average of their duration were observed in the stations located 492nt he coasts of the Oman Sea and the Persian Gulf, and on the Sistan plain in the eastern part of the studied area. The lowest average of heat wave number events and at the same time, the longest average of their duration was observed in the west of the studied area, which includes the two provinces of Kerman and Yazd. The average of the most intense heat waves did not follow specific spatial patterns in this region, and the average of the most intense heat waves in the northeastern (Tabas station), eastern (Zabul station), southeastern (Minab station), and central parts of Sistan and Baluchistan province (Iranshahr station) were observed in the point form. The high potential of this climatic hazard for this part of Iran has been well shown due to the climatological results of the different characteristics of heat waves in the cental and southeastern parts of Iran.

In addition, the trend analysis of long-term changes in five different characteristics of heat waves in the cental and southeastern parts of Iran has indicated the intensifying of all these five characteristics for this part of Iran. On a regional scale, in each decade, 0.5 events have been added to the HWN in the cental and southeastern parts of Iran from 1985–2018. The long-term trend changes in the HWD also indicated an increase of 0.91 days per decade. The HWF has shown more drastic changes than other characteristics of heat waves. In every decade, 61.2 days have been added to the frequency of days contributing to the event of heat waves. This increase in HWF can be a serious warning for the occurrence of more and longer heat waves in the cental and southeastern parts of Iran. The regional average of HWM for the cental and southeastern parts of Iran is 41.2 degrees Celsius, which has increased by 0.1 °C every decade from 1985–2018. The average regional HWA for the studied area was about 43.4 degrees Celsius, and its long-term trend changes indicate an increase of 0.4 °C every decade.

The most drastic changes in the characteristics of heat waves in a station scale were observed in Zabul, Minab, Bandar Abbas, Bandar-e Lengeh, Yazd, Kerman, and Iranshahr stations, respectively. In the meantime, Zabul station in the northern part of Sistan and Baluchistan province has a more dangerous situation than other stations. The most important environmental factors in intensifying the various characteristics of heat waves in this part of Iran are the drying up of three international Hamon lakes, severe and long-term droughts, and the loss of vegetation. Stations located on the southeast coast of the study area such as Minab, Bandar Abbas, and Bandar-e Lengeh also experience the same situation as Zabul. Therefore, politicians and planners should pay special attention to the eastern and southeastern regions of the studied area, because they are the important centers of change in the characteristics of heat waves

These findings show the importance of choosing a suitable index for monitoring different characteristics of heat waves. The *EHF* index is a composite index based on minimum and maximum daily temperatures, which can be one of the suitable indices in this regard. Finally, it is necessary to consider the relationship of these changes with large-scale atmospheric forcing in future studies to gain a deeper understanding of the changes that occurred in the various characteristics of heat waves. In addition, it is necessary to study energy consumption and human health in this part of Iran, which has a dry and super-dry climate.

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