



Spatio-temporal analysis of changes in heat and cold waves across Iran over the statistical period 1966–2018

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Abstract

Climate change is a worldwide issue which has a dramatic influence on temperature, precipitation, glaciers, and water bodies. The climate of the Earth is getting warmer significantly. This, in turn, increases such extreme weather events as heat and cold waves. To understand these two extreme weather events, the data on the mean daily minimum and maximum temperatures were collected from 39 meteorological stations over the period 1966–2018. These stations were selected because of their long-term data records, the lack of statistical deficiencies, and their proper spatial distribution throughout the country. The aim of this study was to investigate the frequency and spatio-temporal changes of heat and cold waves. After forming the time series for heat and cold waves by employing the Baldi approach, and using the non-parametric Mann-Kendall test and Sen's slope estimator, their spatio-temporal variations were investigated. The results showed that the mean daily minimum and maximum temperatures were higher in the recent years and decades. Compared to the data recorded in the 1970s, the maximum temperature increased by about 1.5°C, and the minimum temperature rose by about 1.9°C in the recent years (2011–2018). As a result, the frequencies of heat waves (cold waves) have increased (decreased). In this regard, about 85% of the selected stations showed increases (decreases) in the frequencies of heat waves (cold waves). The station in Yazd exhibited the largest trend in increasing (decreasing) frequencies in heat waves (cold waves) at the 99% significance level.

Keywords Climate change · Global warming · Extreme weather events

Introduction

Following the Industrial Revolution, humans have expanded the use of buried reservoirs or the so-called fossil fuels at an uncontrolled pace due to their need for energy and because of the population growth, the increase in urbanization, and the industrialization of the societies. The use of these non-renewable resources has increased the emission of greenhouse gases. This has been confirmed by climate scientists, who have introduced the theory of global warming (IPCC 2007), what has gradually led to climate change.

Climate change is one of the most complex problems on the Earth in the twenty-first century (Watts et al. 2018; Austin

et al. 2020). The results of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2014 showed that during the years 1880–2012, the average global temperature increased by 0.065–1.06 °C and predicted that by 2081–2100, it will increase by 0.3–1.7°C (under the most optimistic scenario for the emission of greenhouse gases) and by 2.6–4.8°C (under the most pessimistic scenario for the emission of greenhouse gases), compared to 1986–2005. The report also states that carbon dioxide emissions have the strongest radiative forcing and affect the radiation balance and, therefore, the total heat balance of the earth. The evaluations of the Action for Climate Empowerment conducted under the auspices of the United Nations Framework Convention on Climate Change in Iran also suggest that if the carbon dioxide concentration doubles by 2100, then Iran's average temperature will rise by 1.5–4.5°C, and the average precipitation will decline by ten percent (25 mm). This decrease is projected to be as high as 26% compared to the normal situation, especially for cold seasons.

The evidence mentioned above suggests that the climate will be warmer and drier throughout Iran in the coming

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decades than in the historical period. The occurrence of such conditions influences all sectors of the country's economy, but its outlook, together with the special climatic situation in Iran (the rainfall, the relatively warm climate, the unbalanced rainfall distribution, and the high frequency and severity of droughts), will cause major limitations in agricultural production (Hoseini et al. 2013).

Another important consequence of these variations will be the changes in the patterns and frequencies of climate extremes including heat waves and cold spells. In fact, when extreme temperatures persist for several consecutive days, the terms heat wave and cold spell are used. These extreme temperatures may have adverse effects on the ecosystems and also on the social and economic systems (Gosling et al. 2009; Ekamper et al. 2010; Barnett et al. 2012; IPCC 2012; Perkins and Alexander 2013; Herring et al. 2014). Of course, given the discussion on climate change and global warming, there have been extensive studies on heat waves, and less attention has been paid to cold spells (Schar et al. 2004; Feudale and Shukla 2011; Lu et al. 2015; Piticar 2018; Ye et al. 2019). However, numerous studies have been conducted around the world on the significant increasing and decreasing trends in heat waves and cold spells during the recent decades. Here, we mention some of them.

Zhang et al. (2017) studied the trends of heat waves and cold waves in the tropical city Guangzhou, concluding that the frequencies of extremely high temperatures and heat waves are increasing (around 0.17°C and 6.26 days per decade) and that the frequency of cold spells is declining (1.77 days per decade). Tomczyk and Sulikowska (2018) reported that the number of hot days, followed by more frequent heat waves, has increased in the low-lying areas in Germany over the past 50 years (1966–2015). They attributed this to anti-cyclonic circulation. Ye et al. (2019) studied such extreme events as drought, heat waves, and their combination in China. They concluded that since 1990, droughts have become more frequent in some parts of the country, the frequency of heat waves has risen in most places, the occurrence of these two events in combination has also been on the rise, and the rising trend in the combination of droughts and heat waves has been observed throughout the country.

Piticar (2018) examined changes in the trend of heat waves in Chile and found that most weather stations reported significant increases in this trend. Žibera and Ivajnsic (2019) examined the frequency, intensity, and duration of heat waves in the City of Maribor and concluded that all these features of heat waves were increasing. Pai et al. (2017) also found in their study on the process of heat waves (cold spells) across India that the frequencies of these events were increasing (decreasing). They stated that their results were in line with those of other studies reported from around the world. Smida et al. (2019) ranked the vulnerability of major European cities to heat waves and cold spells in the coming decades. They

concluded that most of these cities were susceptible to heat waves and that cold spells would occur in the middle of the present century, but would not be a serious threat.

According to previous studies performed in Iran, the range of daily air temperature and the number of frost days, ice days, cool days, and cool nights in most stations of the Iran Meteorological Organization have negative trends (Rahimzadeh et al. 2009). Ghavidel Rahimi and Ahmadi (2015) showed that the annual maximum temperature of the Abadan station had a positive trend.

Cold waves lead to a lot of damage to agricultural crops. In this regard, Aalijahan et al. (2019) identified days that were less than -15°C using a new method and showed that at the sea level, high-pressure waves from Siberia and west and northern regions coupled with the atmospheric blocking and the northern airflow in the upper levels of the atmosphere led to transmission of cold waves from northern latitudes to the northwest regions of Iran, resulting in very intense and long-lasting cold waves. While in this work, they showed that the cold waves are increasing by a coefficient of 0.0429. Ghavidel Rahimi (2011a), by setting a threshold of -14.93 , identified the extremely cold temperatures of Maragheh station. The results of synoptic analysis on selected days showed 3 circulation patterns including Western pressure high pattern, integrated pressure high pattern, and Siberian pressure high pattern, and the establishment of each of these circulation patterns on the ground also completes and intensifies the role of cold temperature advection and finally causes severe cold weather and thus creates extreme cold temperatures in Maragheh station. Ahmadi and Ghavidel Rahimi (2011), in another study using the Normalized Temperature Deviation (NTD) index, identified 80 days with high extreme temperatures in the Azerbaijan region of Iran. Their study confirms that the NTD method is a suitable method for determining and separating extreme temperatures. According to the study of Ghavidel Rahimi (2011b), it should be acknowledged that temperature advection from high latitudes plays a major role in reducing the temperature and the causes of cold all these days are advection and transitional type.

The above synoptic conditions can be confirmed based on teleconnection indices such as the North Sea-Caspian pattern (Ghavidel Rahimi et al. 2015a) or the Arctic Oscillation Index (Ghavidel Rahimi et al. 2016a). For example, Ghavidel Rahimi et al. (2016a) studied this issue in the northeastern region of Iran and showed a significant and negative (inverse) relationship with the AO index. That is, when the value of the indicator is positive, the temperature is low, and vice versa, when the indicator is negative, the temperature shows the high value. Ghavidel Rahimi et al. (2016b) also examined these results for maximum temperatures. The results of the study also showed a significant and inverse relationship. It is noteworthy that a stronger relationship was

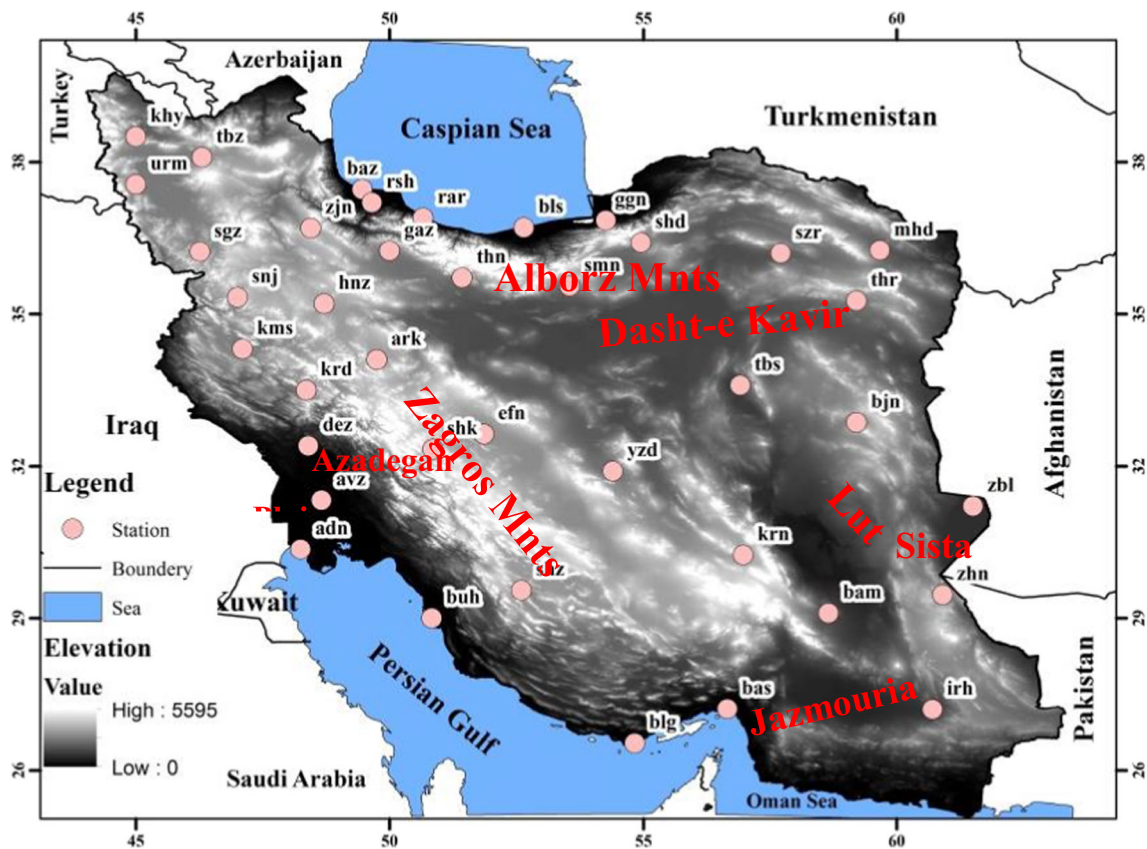


Fig. 1 The study area, its topography, and the meteorological stations providing the studied data

found between the patterns and the monthly temperature data. Increased heat waves will also lead to more fires.

On December 11–13, 2010, one of the largest fires occurred in Mazandaran province in northern Iran. The results of the study of Ghavidel et al. (2016) showed that during the 3-day fire, a pressure center of 1110 hPa on the Persian Gulf and a very low-pressure center on Turkey and Asia Minor were created. The current conditions cause a pressure gradient and ultimately cause the absorption of hot and dry air from the Arabian Peninsula and Iraq, so that it increases the maximum daily temperature and finally provides the conditions for fire. Ghavidel Rahimi et al. (2015b), examining the relationship between Iran's maximum temperatures and global mean land-ocean temperature anomalies, pointed out that the effect of global warming on maximum temperatures in the colder months of the year such as January, December, and November is much less. It is most seen in spring and summer in southern stations. The temperature of the warm period is more affected by global warming than the cold period and indicates an increase in the temperature of the hot period of the year. Even some stations such as Anzali, Urmia, and Khorramabad in some months have the inverse effect of global warming, and their maximum temperature has decreased. Ghavidel Rahimi et al. (2016c) identified heat waves in southeastern Iran using the Fumiaki index and

divided them into three categories: hot, severe hot, and super-hot days. At the same time, the results of their work showed that hot days are increasing. Gang thermal low pressure on the Earth's surface and 850 hPa level and subtropical high pressure on two levels including 700 hPa and 500 hPa cause super-hot days.

The incremental trend of heat waves has not been examined in all studies. According to the findings of Abbasnia et al. (2016), the frequency of heat waves decreases at high thresholds (like the 99th percentile), while their intensity and duration increase.

Therefore, the results of most studies show an increasing (a decreasing) trend in the frequency of heat waves (cold waves). This motivated us to carry out such a long-term study in Iran, which also has a large, wide geographical area. More precisely, our objectives were to do the following in Iran, over a statistical period of more than 53 years (1966–2018), using both the MK test and Sen's method.

- (I) To assess the trends in daily average minimum and maximum temperatures over single years and decades
- (II) To assess the trends in the temperature thresholds of heat and cold waves over single years and a half-century
- (III) To investigate the spatio-temporal variations in the frequencies of cold and heat waves

Table 1 The characteristics of the stations used in the study

Row	Name	Label	Lon. (degree)	Lat. (degree)	Ele (m)	P-Annual (mm)	P-Winter (mm)	P-Spring (mm)	P-Summer (mm)	P-Fall (mm)	T (C)	De Martonne's Index (1926)
1	ABADAN	adn	48.25	30.36	6.6	152.9	74	19.1	0.1	59.7	25.3	Arid
2	AHVAZ	avz	48.66	31.33	22.5	205.3	100.2	21.6	0.2	83.3	26.2	Arid
3	ARAK	ark	49.75	34.1	1755	350.3	161.5	89.3	2.7	96.8	13.6	Semi-arid
4	BABOLSAR	bls	52.65	36.71	-21	879.5	230.5	75.6	170.1	403.3	16.5	Humid
5	FORODGAH BAM	bam	58.65	29.1	1067	64.1	34.8	18.9	1.8	8.6	23	Arid
6	BANDARABAS	bas	56.66	27.21	10	185.5	126.4	14.2	3.6	41.3	27.3	Arid
7	ANZALI	baz	49.46	37.46	-26.2	1874.3	415.4	165.7	424	869.2	16	Sever humid
8	BANDAR LENGEH	blg	54.83	26.53	14.2	151.4	97.6	9.4	4.5	39.9	27.6	Arid
9	BIRJAND	bjn	59.2	32.86	1491	176	101.8	41.7	0.3	32.2	16.5	Arid
10	BOSHEHR	buh	50.83	29	19.6	261.2	123.9	12.5	0	124.8	24.5	Arid
11	ESFAHAN	efn	51.86	32.63	1600.7	121.1	52.2	29.7	2.5	36.7	16.1	Arid
12	GORGAN	ggn	54.26	36.85	13.3	612.1	194.8	132	91.6	193.7	17.8	Mediterranean
13	IRANSHAHR	irh	60.7	27.2	591	117.6	66.5	11	21.6	18.5	27.6	Arid
14	KERMANSHAH	kms	47.1	34.31	1322	456.8	201.5	103.6	1.6	150.1	14.4	Semi-arid
15	KERMAN	krm	56.97	30.25	1753.8	158.9	92	34.7	2.6	29.6	16.9	Arid
16	KHOY	khy	45	38.5	1107.5	305.7	79.8	129.1	24.7	72.1	12.5	Semi-arid
17	KHORAMABAD	krd	48.36	33.5	1125	520.2	242.9	108.6	1.4	167.3	17.3	Semi-arid
18	OROMIOEH	urm	45	37.56	1350	361.4	120.2	130.1	12.4	98.7	11.2	Semi-arid
19	RASHT-FORODGAH	rsh	49.65	37.2	36.7	1369.2	372.9	160.7	266.1	569.5	16.2	Sever humid
20	GHAZVIN	gaz	50	36.25	1278.3	316.7	132.4	86.1	4	94.2	14.3	Semi-arid
21	RAMSAR	rar	50.66	36.9	-20	1221.9	238.7	153.8	272	557.4	15.9	Sever humid
22	SABZEVAR	szr	57.71	36.2	977.6	187.5	97	44.5	2.6	43.4	17.5	Arid
23	SAGHEZ	sgz	46.26	36.23	1522	521.8	206.6	155.1	5.2	154.9	12.3	Mediterranean
24	SANANDAJ	snj	47	35.33	1373.4	484.1	216.6	119.3	1.9	146.3	14.2	Mediterranean
25	SEMNAN	smn	53.55	35.55	1171	137.9	66.1	32.6	5.5	33.7	18.3	Arid
26	TABRIZ	tbz	46.3	38.09	1361	301	93	114.4	17.1	76.5	11.9	Semi-arid
27	TABAS	tbs	56.91	33.6	711	84	45.6	20.4	0.2	17.8	22.4	Arid
28	SHAHREKORD	shk	50.85	32.33	2061.4	320.9	167.1	55.4	2.7	95.7	12.6	Semi-arid
29	ZANJAN	zhn	60.9	29.46	1370	96.2	59.5	17.4	2.3	17	18.5	Arid
30	TEHRAN	thn	51.425	35.716	1190.8	230.2	106.5	48.5	4.9	70.3	17.1	Arid
31	MEHRABAD TORBAT HEYDARIEH	thr	59.2	35.26	1450.8	272.8	152	64.9	1.1	54.8	14.8	Semi-arid
32	YAZD	yzd	54.4	31.9	1230.2	62.7	33.7	13.4	0.5	15.1	19.2	Arid
33	ZABOL	zbl	61.5	31.21	489.2	61.5	43.3	6.2	0	12	22.6	Arid
34	ZAHEDAN	zhn	60.9	29.46	1370	96.2	59.5	17.4	2.3	17	18.5	Arid
35	MASHHAD	mhd	59.66	36.26	990	259.3	125.5	81.3	3.2	49.3	13.8	Semi-arid
36	HAMEDANE NOZE	hnz	48.71	35.2	1679.7	339	143	96.9	3.7	95.4	11	Semi-arid
37	DEZFUL PAIGAH	dez	48.4	32.4	143	391.5	210.4	43.2	0.2	137.7	24.3	Semi-arid
38	SHIRAZ	shz	52.6	29.55	1488	344.2	193.5	36.7	1.6	112.4	17.8	Semi-arid
39	SHAHROOD	shd	54.95	36.41	1345.3	156.5	66.1	52.1	5.6	32.7	14.5	Arid

In simple terms, we outline climate fluctuations in the study region, because analyzing the variation may lead to a better understanding of climate variability in Iran. Therefore, we raise the following questions.

- Has Iran's annual temperature risen over the past half-century?
- Have the temperature thresholds of heat and cold waves changed during the aforementioned statistical period of 53 years in Iran?

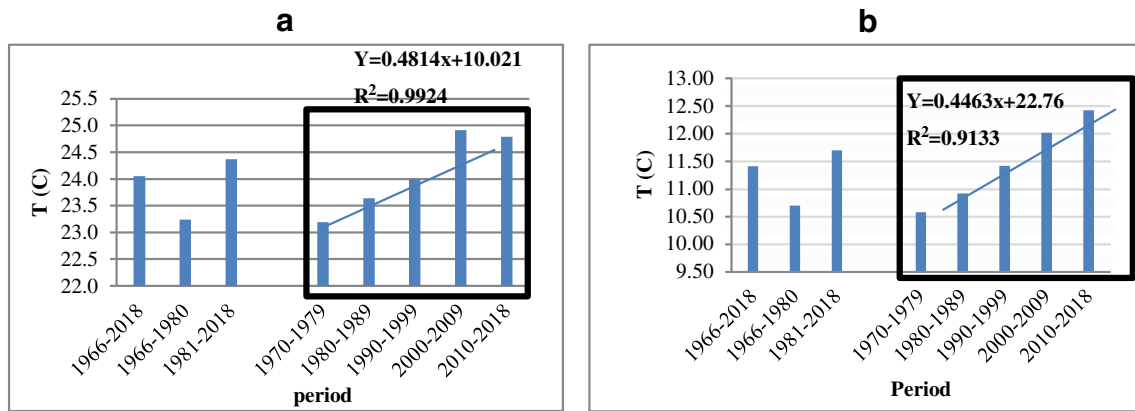


Fig. 2 The average maximum temperatures (a) and minimum temperatures (b), averaging for all stations for the long-term period (1966–2018), the first period (1966–1980), the second period (1981–2018), and in decades (the straight lines denote the corresponding linear trends)

- Finally, did heat (cold) waves have an increasing (a decreasing) trend in the past decades in Iran?

The data and methods

The study area

With a total area of 1.648 million square kilometers, Iran lies between 45–63° East and 25–40° North in the south west of the Middle East. Iran is in the temperate zone in the arid and semi-arid belt of the world and has four distinct seasons due to its wide range of latitude. The climate varies from cool temperate in the north and northwest to subtropical in the south and southeast. Central Iran has hot and dry summers and cool winters. The climate varies with the change in topography across Iran, where a central plateau is surrounded by the two mountainous zones of Alborz in the north and Zagros in the west with elevation ranges of –56 to 5415 m a.s.l (Darand et al. 2015).

The main topographic features of Iran and some of its arid regions are shown in Fig. 1. The Alborz mountain range to the north and the Zagros mountain range to the west of the Iranian plateau prevent moisture from such seas as the Caspian and

the Black and Mediterranean Seas to reach these arid areas. As a result, these dry areas, and generally eastern Iran, receive very little rainfall. The two arid regions of Iran are Dasht-e Kavir (the largest desert in Iran with an area of 256,000km²) and Dasht-e Lut. The Lake Jazmourian is a wetland in south-eastern Iran. However, it has been drastically affected by severe and prolonged droughts and has been turned into a dry lake (Alizadeh-Choobari et al. 2014). According to De Martonne's climate classification, 64.4% of Iran has an arid climate, 25.8% has a semi-arid climate, 5% has the Mediterranean climate, 2.3% has a semi-humid climate, and the remaining areas have humid and very humid climates (Masoodian and Kaviani 2007).

The data

The analysis was conducted with daily values of the maximum (T_{max}) and minimum (T_{min}) air temperatures in the period of 1966–2018 from 39 meteorological stations located in Iran (Fig. 1). These stations were chosen because of their long, robust recorded history and also because they were well-distributed throughout Iran, covering all climatic classes. The characteristics of these stations are listed in Table 1.

Table 2 The results of the paired *t*-test for the two statistical periods (1966–1980 and 1981–2018)

		Paired differences		Std. Error Mean	95% confidence interval of the difference		<i>t</i>	df	<i>P</i> -value
		Mean	Std. Deviation		Lower	Upper			
T-Min	Period_1 - Period_2	–1.00200	.61121	.03195	–1.06482	–.93917	–31.363	365	.000
T-Max	Period_1 - Period_2	–1.13124	.75183	.03925	–1.20841	–1.05407	–28.825	366	.000

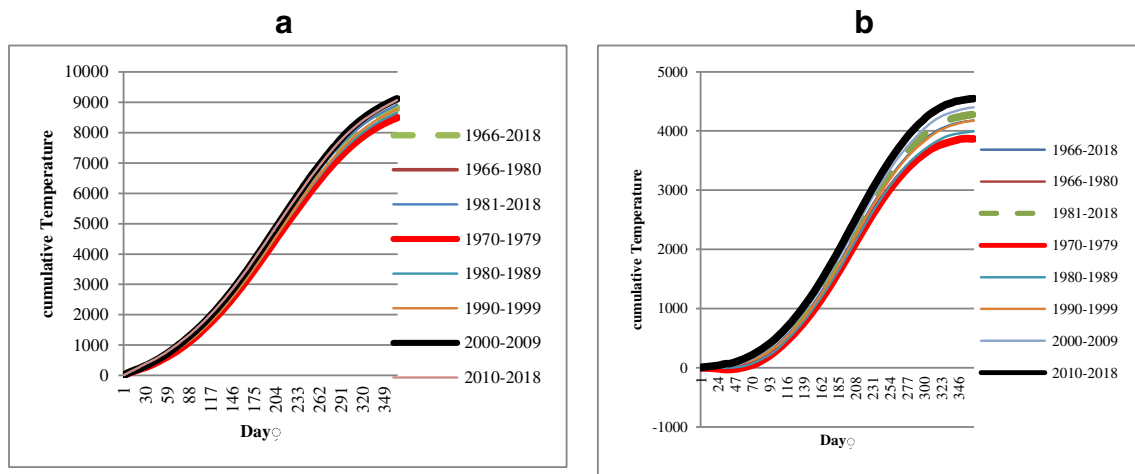


Fig. 3 The cumulative time series of the daily averages of the maximum temperature (a) and the minimum temperature (b), averaging for all stations in the long-term period (1966–2018), the first period (1966–1980), the second period (1981–2018), and in decades

Preparation of the indices

In order to better understand the trends of changes in heat waves and cold spells, the mean daily data on the maximum and minimum temperatures were first divided into two periods, namely, 1966 to 1980 and 1981 to 2018, and also into decade-long periods. A paired *t*-test was used to compare the means of the aforementioned two periods. In fact, we tried to determine if there were any changes in the means of the data before and after the 1980s. In addition, the trend of the changes in these data was studied using regression analysis.

The Baldi approach was used to determine the heat waves and cold spells (Varfi et al. 2009). In this approach, one first identifies the thresholds of heat waves and cold spells using Eqs. (1) and (2), respectively. Based on these thresholds, the days whose maximum (minimum) temperatures are equal to (lower than) the related threshold are considered as days with in a heat wave (cold wave).

$$T_{\max \text{ daily}} \geq T_{\text{mean max daily}} + 1.5 \text{sd}_{\max \text{ daily}} \quad (1)$$

$$T_{\max \text{ daily}} \leq T_{\text{mean max daily}} - 1.5 \text{sd}_{\max \text{ daily}} \quad (2)$$

To determine the temperature threshold for the extraction of heat and cold waves based on the Baldi index, the mean and standard deviation of the data on daily maximum and minimum temperatures at each station were calculated separately, using the following equations.

$$M = \frac{\sum Xi}{n} \quad (3)$$

$$\sigma = \sqrt{\frac{\sum (Xi - m)^2}{n}} \quad (4)$$

In Relation (3), *M* is the mean of the data over the long-run statistical period, *Xi* is the mean daily maximum temperature of the stations, and *n* is the number of days. In Relation (4), *σ* is the standard deviation of the maximum daily temperature at the stations, calculated for the whole statistical period.

After forming the time series for the annual frequencies of heat waves and cold spells using the Mann-Kendall test (Sueyvers 1990; Jaagus 2006) and Sen's slope estimator (Sen

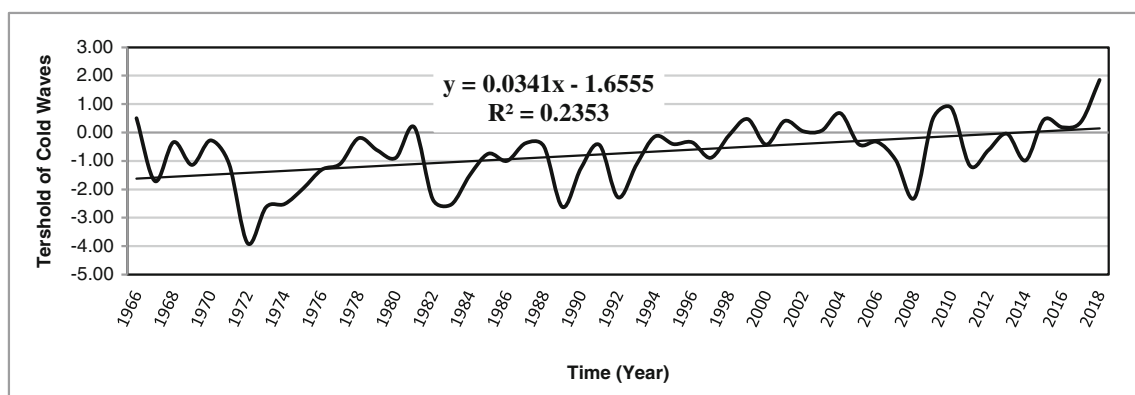


Fig. 4 The time series of cold waves threshold based on the Baldi index (averaging for all stations) during the statistical period (1966–2018)

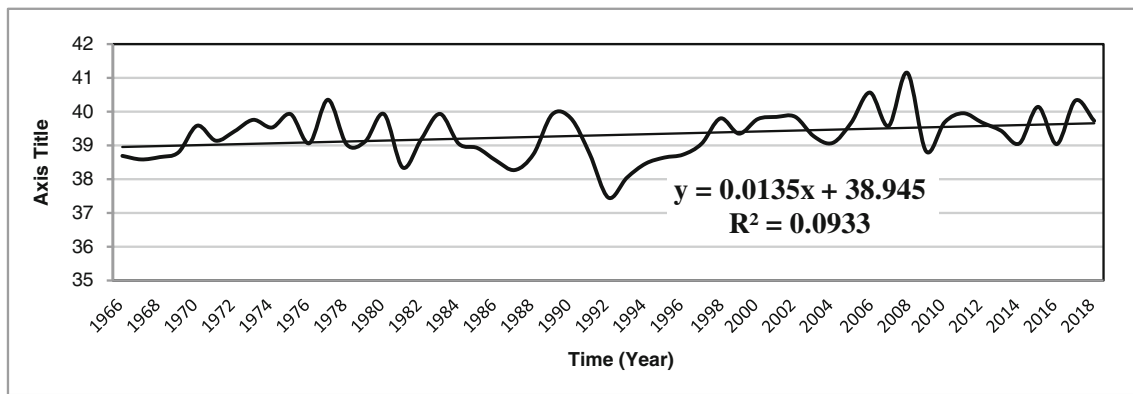


Fig. 5 The time series of heat waves threshold based on the Baldi index (averaging for all stations) during the statistical period (1966–2018)

1968), the trends of changes in these phenomena were determined.

Results and discussion

Figure 2 shows the average maximum temperature (A-2) and the minimum (B-2). Each of these shapes has two separate parts (the second part is separated by a square). They show an increasing trend in the mean values of the minimum and maximum temperatures. In these figures, the long-term period includes all the years we studied (1966–2018). In order to understand the temperature changes, this period is divided into two smaller periods, namely, 1966–1980 and 1981–2018. The first section of figures shows the average temperatures for these periods. The second part of Fig. 2a and b, which is also separated by a square, indicates variations in the decade average of the minimum and maximum temperatures.

According to the long-term period (1966–2018), the average minimum and maximum temperatures in Iran are 11.4 and 24°C, respectively. The average temperature (minimum and maximum) in the first period (1966–1980) and in the second (1981–2018) shows significant changes compared to their long-term values. Thus, in both figures, the average temperature in the first (second) period is less than (higher than) the long-term average. In fact, the selected stations have recorded

higher temperatures in the second period. In other words, the average minimum and maximum temperatures in the second period were compared with the first period. The results of this comparison revealed that the average maximum and minimum temperatures in the second period were, respectively, about 1.5°C and 1.3°C higher than their corresponding values in the first period.

The significance of these changes was assessed by the paired *t*-test. The results of this test statistic are presented in Table 2. This table shows that the *t* value for the data on the mean minimum (maximum) temperatures is −31.36 (−28.825) and that the obtained *P*-value is 0.00 (0.00). Since the *P*-values for both variables are less than 0.05, we conclude that the null hypothesis ($H_0: \mu_1 = \mu_2$) is rejected and the alternative hypothesis ($H_1: \mu_1 \neq \mu_2$) is accepted. So, there is a significant difference between the mean of the first period (1966–1980) and that of the second (1981–2018). This can be a warning to the study area, because rising temperatures will lead to an increase in such extreme events as heat and cold waves.

In order to evaluate the temperature changes more accurately, in the second part of the figure, the average temperatures of the decades have been drawn. As can be seen, the average minimum and maximum temperatures of the decades also reveal increasing trends. The trend lines on the figures confirm this fact. The slope of the increase in the minimum data is greater than that of the maximum data. Therefore, the

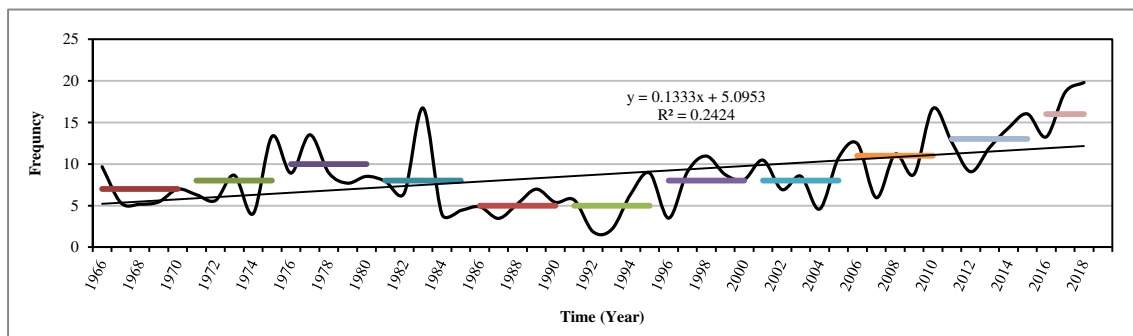
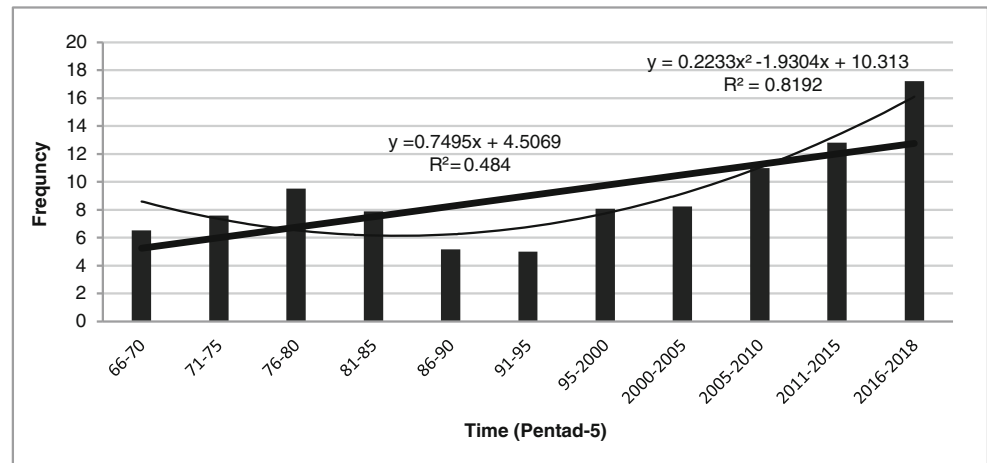


Fig. 6 Annual changes in the frequency of heat waves (1966–2015); the bold and dotted lines represent the year averages

Fig. 7 Pentad variations of the mean annual frequency of heat waves (1966–2018)



increasing trend changes from 0.48 for each decade for the average maximum temperature to 0.44 for the average minimum temperature. Based on the comparison of the average maximum and minimum temperatures in the 1970s with those of the period 2001–2018, we find that the average maximum temperature is increased by about 1.5, and the average minimum temperature is increased by about 1.9°C.

Many regional studies have shown that the temperature is rising; according to Shahid (2010), the mean, mean maximum, and mean minimum temperatures are increasing at a rate of 0.103, 0.091, and 0.097 per decade, respectively. Salman et al. (2017) detected significant increases in the minimum and maximum temperatures at all stations in Iraq.

Figure 3 shows the cumulative values of the daily averages of the maximum temperature (Fig. 3a) and the minimum temperature (Fig. 3b) in the same periods as above. The reason for using the time series for the cumulative data has been to facilitate the comparison. As can be seen in this figure, it is easy to see the increase of temperature time series in the recent periods; the highest temperatures were observed in the recent years, and the lowest temperatures were recorded during the first decade (1971–1980). Based on the distance between the two bold lines shown in the figures, it can be seen that the rate

of increase in temperature was much higher in the minimum temperature values than in the maximum temperature values. In the figures, the rates of increases in the minimum temperatures are much higher than those in the maximum values. In fact, the average daily minimum temperature over the days of the recent decades has been higher. In other words, there has been a sharp decline in the number of cold nights. In general, in both datasets, the first decade (1971–1980) had lower temperatures, and the more recent decades had higher temperatures.

The time series analysis of T_{\max} and T_{\min} shows that the temperature has a positive trend. Heat and cold waves are functions of the temperature. As a result, the characteristics of these events, such as the temperature threshold and frequency, will change. In this section, using the Baldi index, the annual temperature thresholds for heat and cold waves are calculated separately for all stations. In order not to prolong the research, we avoided presenting the threshold time series separately for each station; we calculated the average for all stations.

Figures 4 and 5 show the time series of temperature thresholds for determining heat and cold waves for all stations. As can be seen in these figures, these thresholds exhibit a

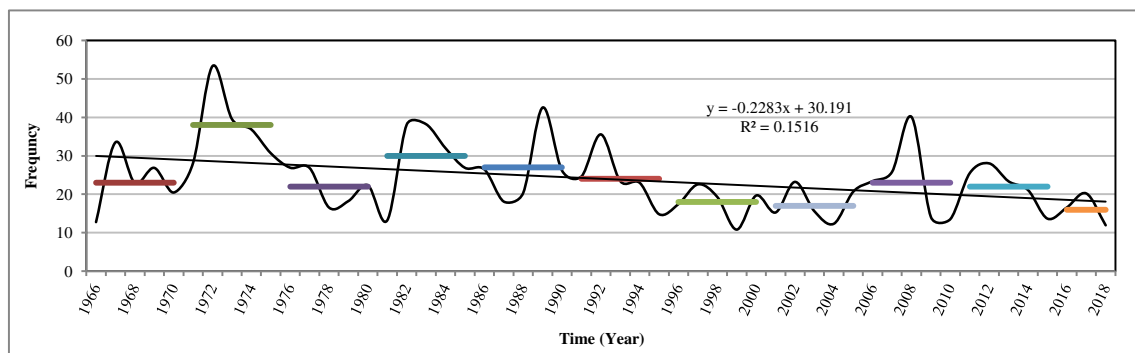
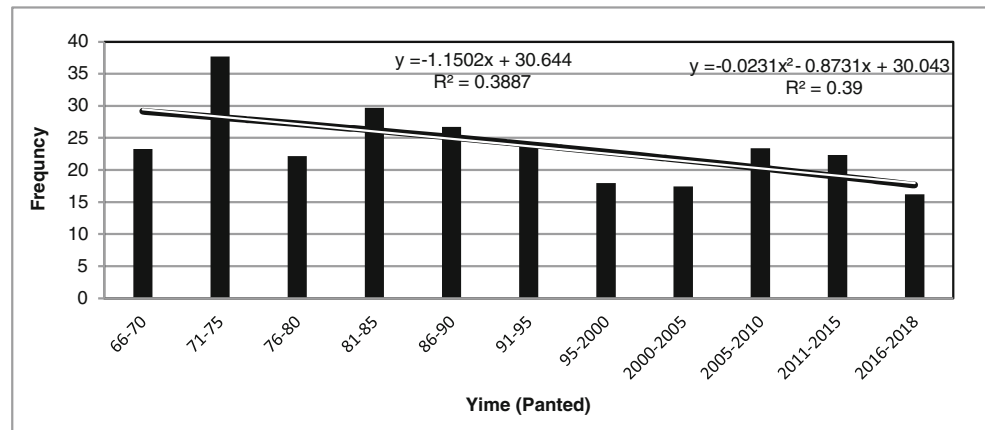


Fig. 8 Annual changes in the frequency of cold waves (1966–2015); the bold and dotted lines represent the year averages

Fig. 9 Pentad variations of the mean frequency of cold waves (1966–2018)



fluctuating behavior, because the meteorological variables do so. What is certain, based on these two figures, is that the threshold values for the heat waves and cold spells will increase due to the rise in the temperatures recorded at the stations. The rising trend in the threshold for the cold spells has been increasing at a steeper slope compared to that for the heat waves. In fact, the difference between the minimum and maximum temperatures is declining. Since the data on the mean daily minimum temperature was used in the calculation and detection of the threshold for cold spells, this increase represents the reduction of colder nights, because the minimum temperature that occurs in the night is mainly an increasing trend (Fig. 4). Figure 5 presents the changes in the time series of the heat waves. The mean daily maximum temperature was used to calculate this threshold. Considering the increasing trend in this threshold, we notice that the number of warmer days has also been increasing. In addition, based on both figures, the number of heat waves (cold spells) will increase (decrease). The following section will deal specifically with the frequencies of heat waves and cold spells.

As a rule, when the temperature threshold changes, the characteristics of heat waves, such as their frequency, change. Based on the temperature threshold, the annual frequencies of heat and cold waves were calculated. Figure 6 shows the time series of the mean annual heat waves in Iran over the 53-year period, from 1966 to 2018. As shown in this figure, during the early years almost up to 1990, the annual fluctuations lacked any trends, but an increase in the number of heat waves can be observed since 1990. In addition to the oscillating behavior, the highest frequency of heat waves was calculated for 2018. Almost all of the high-frequency heat waves have occurred in the last 20 years (except in 1983). The years 2018 and 2010 have the highest number of heat waves. It is worth mentioning that according to the report of the Meteorological Organization, 2010 was the world's seventh hottest year, and 2018 was the fifth hottest year on record (<https://www.climatecentral.org/gallery/graphics/top-10-warmest-years-on>

record). To better explain the matter, the pentad average of heat waves is also shown in Fig. 7.

Clearly, the trend line shows an increasing trend in the number of heat waves in the recent years. The coefficient of this increase is about 0.75. Over the last 53 years, the highest heat waves have occurred in the last four periods, from 1995–2000 to 2016–2018. The trend line of the quadratic function testifies this claim. Such a graph was also drawn for cold waves. Unlike heat waves that show a rising trend, the time series of cold waves indicates a declining trend. This means that the frequency of cold waves is decreasing. Cold spells represent cold nights and minimum temperatures. Based on this figure, cold spells are generally decreasing in Iran, exhibiting the negative slope of about -0.22 . The number of cold spells has been declining from around the beginning of the 1980s. This decline has continued until 2006, when a short-term rising trend is observed, although this increase is not greater than the total average frequency of cold waves. However, the number of cold spells again decreased over time, and the smallest number of cold spells was that of the last 3 years (2015–2018), unlike heat waves (Figs. 8 and 9).

Since Iran is located in the subtropical region, and is affected by tropical and extra-tropical systems, various systems enter Iran from different parts of the country. These include the subtropical high-pressure system and Pakistan's low-pressure system during the warm season, and the Siberian high-pressure system, the Mediterranean low-pressure system, Sudan's low-pressure system, Black Sea's high-pressure system, etc., which enter the country during the cold season (Alijani 1997; Masoodian and Kaviani 2007). Figure 10 shows the rates of monthly changes in the frequencies of heat waves and cold spells. We witness most of the cold spells during the cold season of the year and the majority of heat waves during the summer. The frequency of heat waves is lower than that of cold spells (Fig. 10). This is due to the location of the country in the subtropical region. Normally,

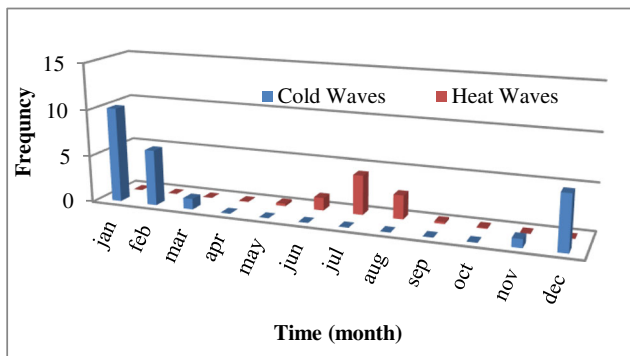


Fig. 10 The mean monthly frequencies of cold and heat waves in Iran during 1966–2018

Iran has a warm and dry climate and usually experiences higher temperatures. Most of the heat waves (cold spells) occur in July (January).

A significant feature of natural hazards is their specific geographic location. Since most extreme geophysical events can be defined spatially, mapping their precise location enhances our knowledge of the risks and potentially exposed population (Montz et al. 2017).

Figures 11 and 12 show the spatial distribution of the annual frequencies of cold and heat waves, respectively. Figure 8 indicates that the lowest annual frequency of cold waves (22 days) belongs to the northern parts of Iran and that the highest (28 days) belongs to the mountainous areas southeast of Iran, including Bam and Kerman Counties, and also to the southwest of the country in Dasht-e Azadegan. The spatial distribution of heat waves demonstrates that the highest annual frequency of these phenomena occurred in the mountainous areas of the northwestern parts of the country.

Based on these two figures, we may conclude that both phenomena are functions of latitude and altitude. In fact, heat and cold waves are inversely related to latitude. The reason for the high frequency of cold waves in southern Iran is that these areas are normally exposed to higher temperatures, due to their lower latitude and proximity to tropical regions. Therefore, the fact that these areas have temperatures lower than the standard deviation of the region is considered abnormal, because they have low latitudes. Therefore, most of the cold spells are observed in this region, unlike the heat waves, which are mostly observed in higher latitudes.

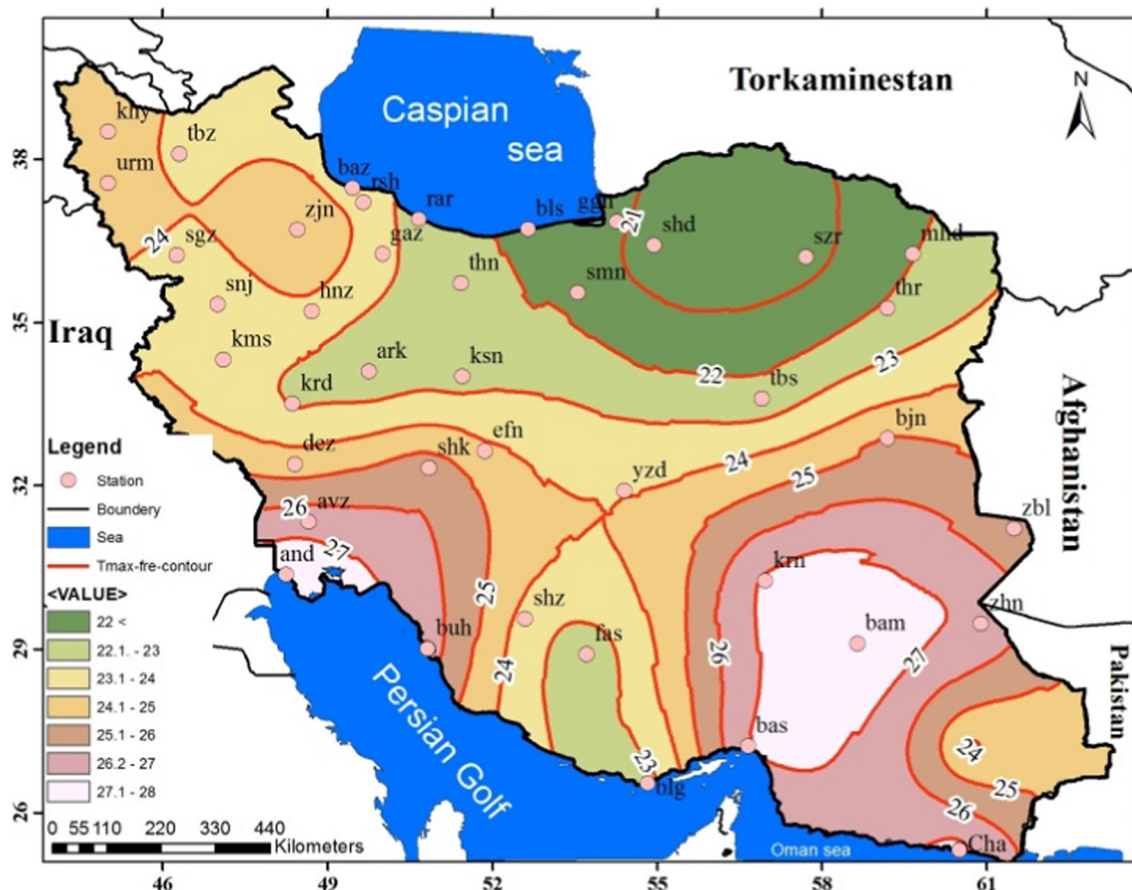


Fig. 11 The annual frequency of cold spells during the statistical period



Fig. 12 The annual frequency of heat waves during the statistical period

We have noticed so far that the temperature thresholds determining heat and cold waves based on the Baldi index are changing and exhibit rising trends due to the increases in the average minimum and maximum temperatures. As a result, the frequency of heat waves (cold waves) has increased (decreased).

This section tries to determine the spatial trends in heat and cold waves. Figure 13 shows the spatio-temporal variations in heat waves. Most of the studied stations indicated increasing trends in heat waves. Statistically, about eighty percent of them showed that the frequency of heat waves was increasing. The existence of decreasing and increasing trends has been investigated based on the Mann-Kendall test, and the results have been tested at different levels of significance, namely, 99%, 95%, and 90% (marked in the figures with the star symbol). About 10% of the stations (4 stations), including the Torbat-e-Heydariyeh, Ramsar, Shahrekord, and Sasez stations, exhibited decreasing trends. Of course, the negative trend of the Sasez station (-0.05) is not significant. Meanwhile, the Hamedan, Iranshahr, Bandar Lengeh, and Anzali stations were without trends. The magnitude of the line slope in the heat waves series varied between (+) 0.333 day per annum at

the Babolsar station and ($-$) 0.2 day per annum at the Torbat-e-Heydariyeh station. These stations each had a significance coefficient above 99%. In general, more than 30% of the stations each had a line slope above 0.2 (the average line slope).

Figure 14 shows the spatio-temporal variations in cold spells. Like heat waves, about 80% (most) of the studied stations showed significant decreasing trends in cold waves, and about 15% ($n=6$) of them (those in Gorgan, Saghez, Shahrekord, Khoram-Abad, Bandar Abbas, and Birjand) exhibited increasing trends in the number of cold waves. The remaining stations, namely, Iranshahr and Khoy, were without trends. The largest increasing trend in cold waves belonged to the Yazd station at the 99% significance level. The Yazd station has a hot and dry climate. At this station, both heat waves had an increasing steep slope (about 0.231), and cold waves were decreasing at a rate of 0.647. Therefore, these conditions indicate that this station is moving towards a drier and more continental climate.

Cold waves have a higher rate of change compared to heat waves, so that the slope of the line between 0.389 and 0.647 is changing. It is worth mentioning that some stations, especially the stations adjacent to the southern coast, such as Bandar

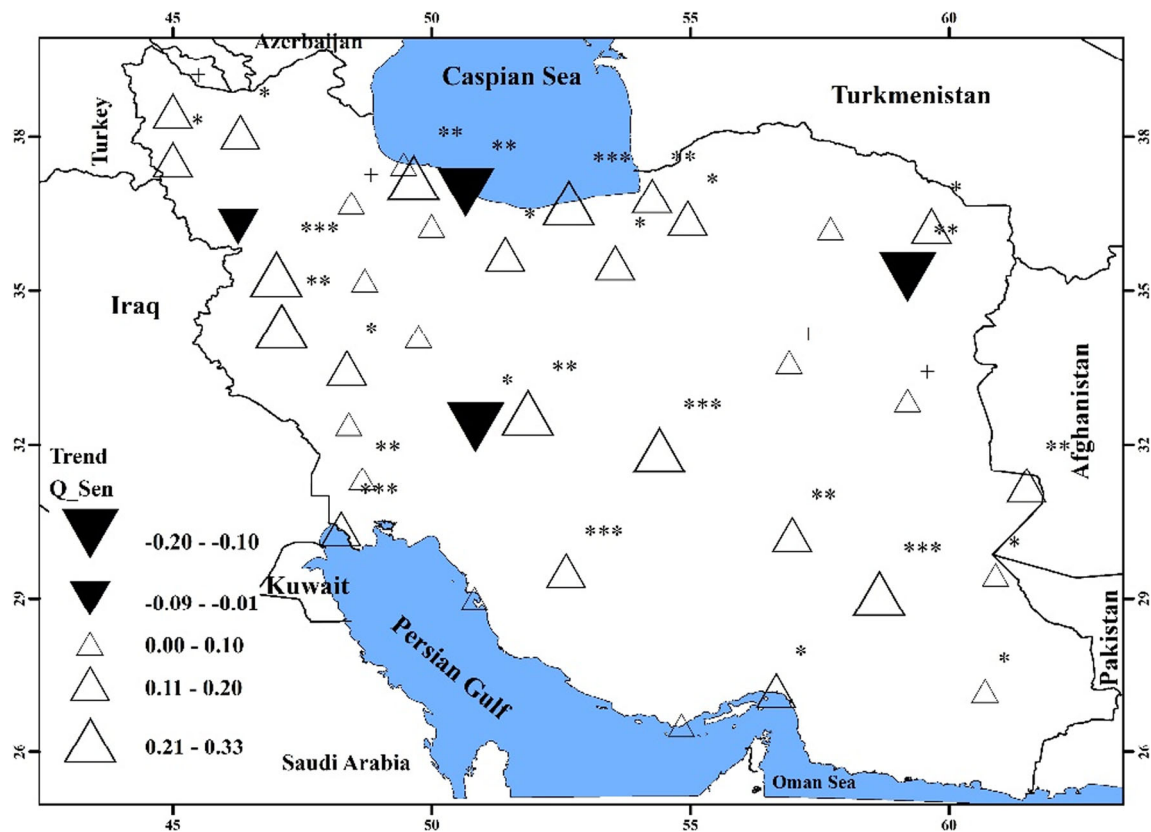


Fig. 13 The map showing the trends of changes in heat waves during 1966–2018 (if the trend is at *** $\alpha = 0.001$, ** $\alpha = 0.01$, * $\alpha = 0.05$, and + $\alpha = 0.1$ level of significance)

Lengeh and Bushehr, did not show a trend in the frequency of heat waves, but their cold waves had a negative trend. This means that cold nights were declining. These stations are in a hot and humid climate.

Conclusion

In this study, the Baldi approach was used for the spatio-temporal analysis of heat waves and cold spells. After forming the time series of heat waves and cold spells, the trends of their changes were calculated using the Mann-Kendall test and Sen's slope estimator. In the first section of the study, the average daily temporal variations in the minimum and maximum temperatures were examined. For this purpose, the employed data were divided into two long-term periods, namely, 1966–1980 and 1981–1998, and then were compared. The data were also compared in decade-long periods. The mean temperature of the first period was higher than that of the second in both variables. The difference between the two periods showed tangible increases in the minimum and maximum temperatures. As stated in the Introduction, this

increasing trend was in line with many studies conducted around the world.

Most of the average daily rise in the temperature has happened since the 1980s. The increases in both the minimum and maximum temperatures were also much more noticeable in the decade-long time series. On average, for the whole country, the minimum temperature and the maximum temperature have increased by 1.9°C and 1.5°C, respectively. Consequently, changes have occurred in the frequencies of heat waves and cold spells. Heat waves and cold spells exhibited almost fluctuating behaviors before the 1980s. However, following the 1980s, they have had increasing and decreasing behaviors, respectively. This is much more tangible in heat waves compared to cold spells. In general, both heat waves and cold spells have exhibited tangible changes.

Declarations

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

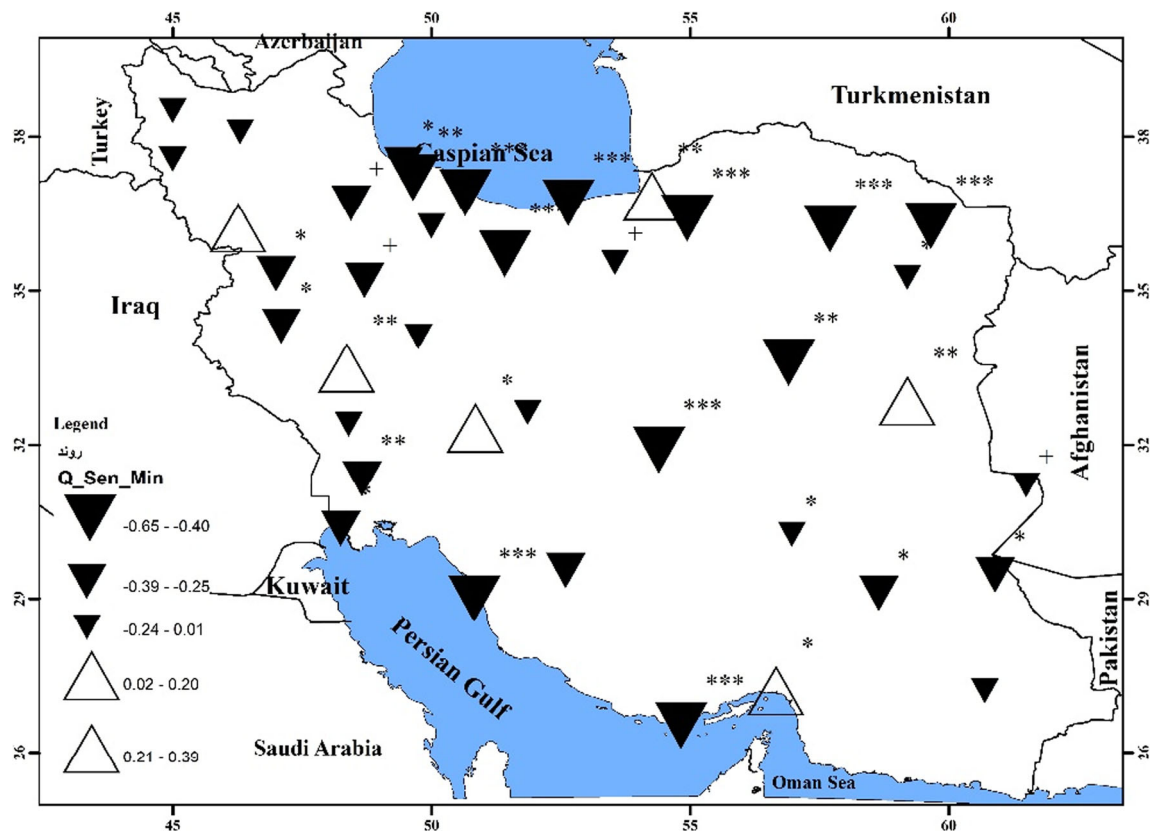


Fig. 14 The map showing the trends of changes in cold spells (1966–2018) (if the trend is at *** $\alpha = 0.001$, ** $\alpha = 0.01$, * $\alpha = 0.05$, and + $\alpha = 0.1$ level of significance)

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