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Winter warming detection using temperature and precipitation anomalies in arid and semi-arid areas

Negar Siabi, Mohammad Mousavi Baygi, Seyed Majid Hasheminia and Mohammad Bannayan

ABSTRACT

Extreme winter warming can affect many aspects of environmental and human related activities. It can be disastrous, especially in arid regions. However, no specific research has been carried out on detecting winter warming in Iran. To address this research gap, this study was performed to investigate winter warming in the arid and semi-arid areas located in northeastern Iran. For this purpose, anomalies of minimum and maximum daily temperature, average daily temperature, mean daily temperature range and mean daily precipitation were studied on monthly, seasonal, annual and decadal scales. Along with this, the trend in the data was analyzed using the Mann–Kendall (MK) test. The results showed that since the 1990s there has been a significant increase in temperature positive anomalies at most stations. In addition, the precipitation anomaly mutations occurred later than temperature. In most cases the increase in winter anomalies was higher than the average annual anomalies. As an example, the maximum winter temperature anomaly increased from 0.38 °C in the 1990s to 2.07 °C in the 2000s at Mashhad station. Due to the simultaneous increase in anomalies at most stations, the detected winter warming is more likely to be the result of global warming rather than local synoptic climate.

Key words | anomaly, climate change, Iran, precipitation, winter warming

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HIGHLIGHTS

- This is the 1st study solely dedicated to assessing the winter warming phenomenon on a local scale in Iran.
- The present study confirmed that winter warming has occurred since the 1990s.
- The warming time in every decade occurred earlier than the previous decade.
- The precipitation's anomaly mutation occurred later than the temperature's.
- The quantification of winter warming in this paper can provide valuable information for water management in arid areas.

INTRODUCTION

The global climate balance has been shaken by the impact of human activities. According to the Intergovernmental Panel on Climate Change's (IPCC) fifth report, over the past 100 years, the average global surface temperature has increased by 0.85 °C in the period of 1880–2012 (IPCC 2014). Climate change studies confirm the high impact of this phenomenon on the environment, water resources, droughts, floods, agriculture, industry and health (Adams *et al.* 1998; Kang *et al.* 2009; Zwiers *et al.* 2013; Bannayan *et al.* 2014; Hatfield & Prueger 2015; Choi *et al.* 2020). Among all human activities, agriculture is the most climate dependent sector, especially in the arid and semi-arid regions of the world. Temperature and precipitation are considered to be the key factors influencing the agricultural activities. Crop

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growth, development rates, planting time, etc., can be affected by these factors (Bannayan *et al.* 2004; Choi *et al.* 2020). In addition to global climate change, many local and regional trends in some parts of the world have been observed as a result of the changing seasonal and annual patterns of temperature. One major circumstance to consider is the unusual fluctuations of temperature in different seasons of the year. Several studies have shown that in the last two decades winter temperatures have increased more rapidly than in other seasons of the year (Balling *et al.* 1998; Otterman *et al.* 2002; Croitoru *et al.* 2014; Hillebrand & Proietti 2017; Zhao *et al.* 2020). A further increase in winter temperatures as compared to other seasons of the year is expressed as 'winter warming'. According to the studies performed by Karl *et al.* (1993), global temperatures are rising, especially in the winter season. The average rise of minimum temperature from 1951 to 1990 was found to be 2.9 °C, while in the summer it was only 1.3 °C. Most parts of the world have been displaced in terms of temperature variations. These changes are more evident in the northern hemisphere and in the seasons that have less solar radiation (Houghton *et al.* 1996). According to the findings of researchers, the winter warming of the northern hemisphere was associated with atmospheric circulation anomalies during 1977–1994 (Wallace *et al.* 1996; Zhang *et al.* 1997). In addition, the warming trend in the middle latitudes of Asia having arid and semi-arid climates (likewise the major parts of Iran) in the months of November–March (cold seasons) with an increase of 2.4 °C was more than the rest of the year (IPCC 2014). Tangborn (2003) showed that in the northern hemisphere, a significant increase in winter temperatures has definitely occurred during the period of the winter solstice and the spring equilibrium since 1985. Chung & Yoon (2000) analyzed the annual temperatures for Korea over a period of 23 years (1974–1997) and showed an increase of 1.5 and 0.58 °C in urban and rural areas per decade, respectively. Their results also showed a temperature increase in winter more than other times of the year. Quintana-Gomez (1999), using the maximum and minimum temperature data of 11 stations in Venezuela and Colombia for the period of 1918–1990, showed that the minimum temperatures increased, while the daily temperature ranges in most stations ware reduced. Rahimzadeh & Askari (2004) used temperature data of 33 synoptic stations across Iran from 1951 to 1997 in order to study the difference between the changing rates in minimum and maximum temperatures and the temperature range. They concluded that the minimum and maximum temperatures were increased at different rates. Furthermore, it was observed that the temperature range in Mashhad and Birjand stations showed a decreasing trend. Raziei *et al.* (2005) examined the precipitation trend in arid and semi-arid regions of Iran by utilizing the Mann–Kendall (MK) method. Their study showed that the annual precipitation trend was negative at some stations, which could indicate a decline in precipitation in recent years. However, they concluded that there was no sign of climate change in the study area because of the observation that negative trends were not statistically significant in most stations. Tabari & Hosseinzadeh Talaee (2011b) investigated the seasonal and monthly rainfall changes in 41 stations for the period of 1966–2005 in Iran. Their results showed an increase in annual rainfall in more than half of the stations and a significant decrease in seven stations. The trend was positive at Mashhad station (+0.036 mm/year). Most trends were decreasing in the winter season, and the decreasing trends were significantly higher in winter than other seasons. Kousari *et al.* (2013) studied the annual, seasonal and monthly trends of maximum temperature at 32 synoptic stations during 1960–2005 in Iran. They concluded that there are significant positive trends in the warm months and the warm seasons in the northeast, west and southeast part of Iran. There were no noticeable trends in cold seasons and cold months. They also found that the upward trend had begun since 1970 and reached its peak after 1990. Ghasemi (2015) examined Iran's temperature changes during the 1966–2010 period using the MK test. According to his findings, in most parts of Iran there was a positive temperature trend at the rate of 0.09–0.38 °C per decade. Also, he found that the minimum temperature trend rate was more than the maximum temperature. Furthermore, he realized that the spring and summer temperature trends were more significant than the winter season. Zarenistanak *et al.* (2014) examined the time series precipitation and temperature during the period of 1950–2007 in Iran. They found that in the case of precipitation the negative trends were not significant. However, some positive trends were found to be significant. An increasing trend was observed in the temperature variables. This trend was more significant for maximum temperature and winter season. In addition to the significant increase in maximum and minimum temperature trend in Iran, Fallah-Ghalhari *et al.* (2019) reported significant negative trends in the indices of cold days and cold nights on a seasonal scale at most stations from 1976 to 2005. Lorenz *et al.* (2019) also concluded that days with extreme heat and heat stress have tripled over Europe from 1950 to 2018. Besides this, they found significant warming trends of 0.33 and 1 °C per decade in hot and cold extremes respectively. Similar results were also obtained by Khan *et al.* (2019) and Zhao *et al.* (2020) in Pakistan and China respectively.

Based on a study by Toreti *et al.* (2010), the modest and almost subtle changes of the winter series trend makes it difficult to detect and interpret warming or cooling in such series. This is despite the fact that the trends of the warmer seasons (especially in the summer) are readily apparent in most of the relevant studies, and the significant decrease or increase has been reported in most studies. However, in general, few studies have been conducted solely on winter warming.

The aim of this paper was to detect the winter warming by examining the daily temperature and precipitation anomalies. This study was conducted on a local scale. According to the IPCC's fifth report (2014), performing more local and regional climate change studies is necessary at the present time. It is worth noting that the majority of conducted research on this subject considered only the common synoptic weather stations in Iran while in this research fewer studied stations are also considered in the arid and semi-arid areas. Another explicit aspect of this study was the examination of five climatic variables, whereas in most other studies only one or two variables have been investigated. The selected variables are considered to be the most influential variables on environmental and agricultural activities in the study area (Bannayan *et al.* 2011; Bannayan *et al.* 2014; Nouri *et al.* 2017).

METHODS

Data and study area

In order to detect the climate change and winter warming phenomenon, daily temperature (maximum and minimum) and precipitation data were collected since the establishment of each station up to 2009 for six synoptic stations. It should be noted that for the trend and mutation analysis, the long-term average of variables was also calculated on monthly, seasonal, annual and decadal time scales using daily datasets. We have been very rigorous in the selection of data, and only weather stations with complete data and complete years were selected among all stations of the region. The characteristics of the studied stations are presented in Table 1. The study area is located in Khorasan Razavi province in northeast Iran, between 57°43′ and 61°10′ longitude and 35°16′ and 37°40′ latitude, as shown in Figure 1. The area has been classified as arid and semi-arid climates in the Koppen climate classification system (Salehnia *et al.* 2018) with complex topography. The elevation of the studied area varies between 213 and 3,298 m above sea level.

Mann–Kendall (MK) test

The first step in detecting climate fluctuations is the use of statistical tests on the long-term series of climatic variables. One of the tests used for this purpose is the MK test. This nonparametric test is used to detect trends in the time series of meteorological and hydrological variables (Yue & Pilon 2004; Tabari & Hosseinzadeh Talaee 2011a). The most important feature of this method is its applicability to time series that do not have a specific distribution. However, the auto correlation effect must be eliminated. A positive auto correlation in the time series may cause major uncertainty in trend analysis (Von Storch 1995). For this purpose, the Pre-Whitening technique was applied prior to applying the MK test (Von Storch 1995).

In the MK test, the values associated with each component are used in the time series. In other words, the

Table 1 | Characteristics of the selected synoptic stations used in the study

Station name	Longitude (°E)	Latitude (°N)	Elevation (m)	Period
Quchan	58.30	37.40	1,270	1984–2009
Kashmar	58.28	35.12	1,110	1986–2009
Mashhad	59.38	36.16	999	1951–2009
Sabzevar	57.43	36.12	943	1954–2009
Sarakhs	61.10	36.32	280	1984–2009
Torbat Heydariyeh	59.13	35.16	1,451	1959–2009

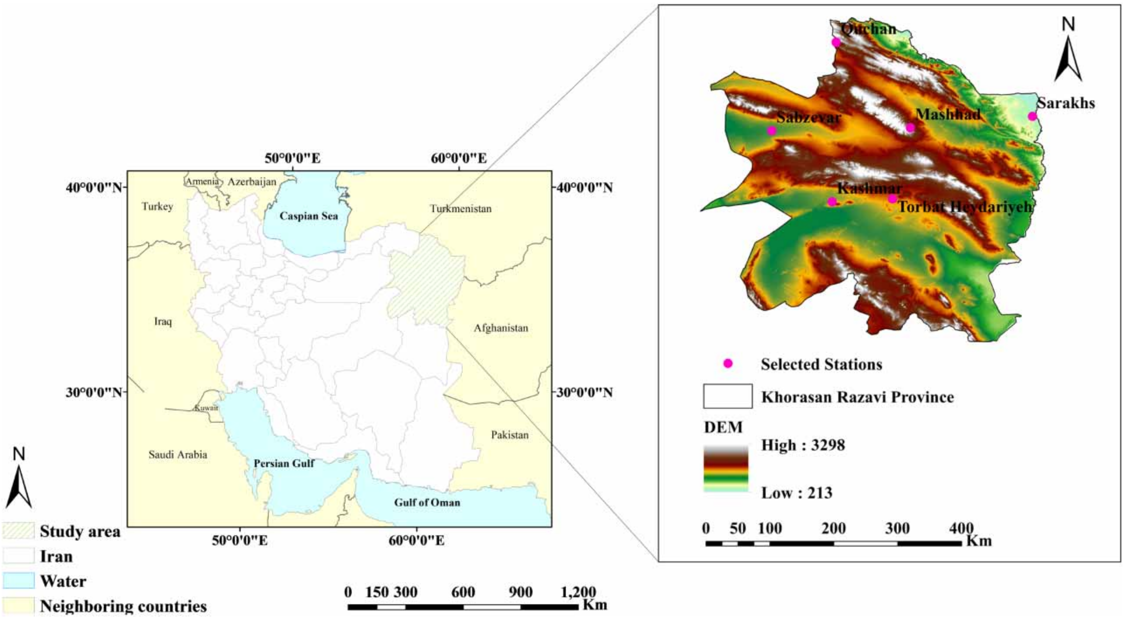

Figure 1 | The study area and the geographical distribution of meteorological stations.

statistical series are arranged in ascending order and then each of them would be assigned a rank, the ranking of which can be between 1 and n (i.e. total number of values). The Kendall statistics are calculated from the following equation:

$$\tau = \frac{4P}{n(n-1)} - 1 \quad (1)$$

In Equation (1), τ is the Kendall statistics, n is the total number of values in the time series, and P is the sum of the number of ranks greater than n_i that are placed after n_i. The value of P can be obtained from Equation (2):

$$p = \sum_{i=1}^{n} n_i \quad (2)$$

For a random set, the mathematical expectation of τ is equal to zero and its variance is determined using the following equation:

$$\mathrm{Var}(\tau) = \frac{4n+10}{9n(n-1)} \quad (3)$$

In order to assess the significance of statistic τ, Equation (4) is used for comparison with τ:

$$(\tau)_t = 0 \pm \ \tan\sqrt{\frac{4n+10}{9n(n-1)}} \quad (4)$$

In the above equation, tan is equal to the normal value (the standardized statistics Z) and it is equal to 1.96 with a 95% confidence level. If this value is applied, then $(\tau)_t$ equals to ± 0.21. According to the critical values of $(\tau)_t$, different states must be considered. Therefore, if the τ value varies between positive and negative 0.21, there are no significant trends in the series and the series are considered random. If $\tau < (\tau)_t$ or, $\tau < -0.21$ then it represents the negative trend in the series, and if $\tau > (\tau)_t$ or $\tau > +0.21$ then a positive trend in the series exists.

Mutation test

In this study, time series abrupt changes (mutation) were investigated using anomalies of variables. Anomalies are more important than absolute values of variables in climate change studies (www.ncdc.noaa.gov/monitoring-references/dyk/anomalies-vs-temperature). Parameters like a station's location or elevation will have less effect on anomalies than the average of absolute data. Anomalies of maximum daily temperature (ΔT_{max}), minimum daily temperature (ΔT_{min}), the daily temperature range (ΔT_r), the daily average temperature (ΔT_a), and mean daily precipitation (ΔP) can be calculated by the following steps. First, the average of the maximum and minimum temperatures in 24 hours (i.e. daily average temperature (T_a)) and the difference between the maximum and minimum temperatures in 24 hours (i.e. daily temperature range (T_r)) for each day (d) of each year (Y) and each weather station (S) were calculated using Equations (5) and (6), respectively:

$$T_a(d, Y, S) = (T_{max}(d, Y, S) + T_{min}(d, Y, S))/2 \tag{5}$$

$$T_r\,(d, Y, S) = (T_{max}(d, Y, S) - T_{min}(d, Y, S)) \tag{6}$$

Thereafter, the long-term average ($V_{kB}(d, S)$) for each day (d) and each station (S) at base period (B) was determined. A different base period for each station was selected because of the differences in the time of observations. For example, at Mashhad station, base period average (1951–1980) and anomaly was calculated for each variable (V_k) as:

$$V_{kB}(d, S) = \sum_{1951}^{1980} (V_k(d, Y, S))/30 \tag{7}$$

$$\Delta V_k(d, Y, S) = V_k(d, Y, S) - V_{kB}(d, S) \tag{8}$$

In the above equations (k) is the number of each variable, which in this study was $k = 1, \ldots, 5$. Same steps were used for all stations to calculate the variables' anomalies.

RESULTS AND DISCUSSION

Maximum temperature analysis

The MK test results on the time series of maximum temperatures are presented in Table 2. According to this table, a significant upward trend was observed in Kashmar, Quchan, Sabzevar and Sarakhs stations at 95% confidence level. Mashhad station had a significant upward trend at a confidence level of 99%, while Torbat Heydariyeh station was found to be without a trend. These results nearly agree with the studies by Tabari & Hosseinzadeh Talaee (2011a) and Fallah-Ghalhari *et al.* (2019), in which there was a significant trend in Mashhad and Sabzevar stations. In addition, the results are slightly inconsistent with Kousari *et al.* (2013). They examined the maximum temperature during the 1960–2005 period, and found an increasing trend at Mashhad and Sabzevar stations and decreasing trend at Torbat Heydariyeh station. Current trends were not significant.

Among all the studied stations, Mashhad, Sabzevar and Torbat Heydariyeh stations have the longest statistical period. Therefore, these three stations were selected to show the visual results. The annual time series and linear trends of maximum temperature at these stations are shown in Figure 2. According to this figure, the maximum temperature trend at Mashhad and Sabzevar stations was positive, however, this trend was found to be negative at Torbat Heydariyeh. The results are consistent with the research by Soltani & Soltani (2008) and Fallah-Ghalhari *et al.* (2019). Tabari & Hosseinzadeh Talaee (2011a) also achieved similar results between 1966 and 2005. According to latter researchers, inverse trends at two adjacent stations (Mashhad and Torbat Heydariyeh) may be explained by different impacts of human and natural factors, dissimilar

Table 2 | The MK test results for maximum temperature variable at 95 and 99% confidence levels

T_{max} (°C)	Mashhad	Kashmar	Quchan	Sabzevar	Sarakhs	Torbat Heydariyeh
P-Value	0.087	0.025	0.008	0.038	0.009	0.136
Z-Mk	1.353	1.95	2.380	1.767	2.358	–1.094
Trend	** +	* +	* +	* +	* +	0

(+) = Positive trend, (–) = Negative trend, (0) = No significant trend, (*) = Significant level of 95%, (**) = Significant level of 99%.

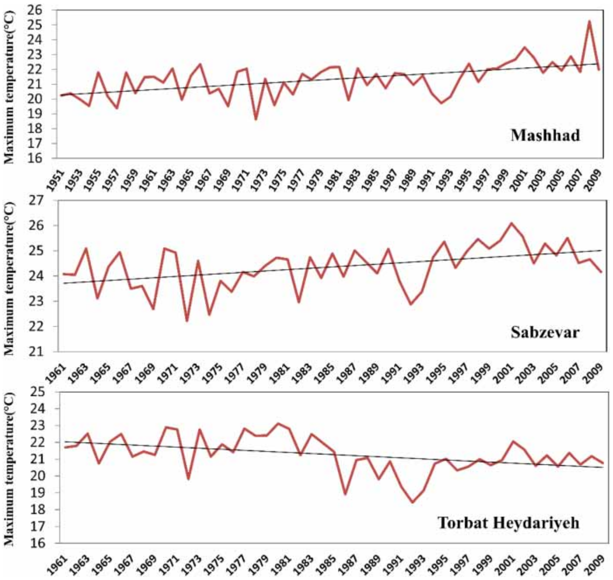

Figure 2 | Time series and linear trends of maximum annual temperatures at selected stations.

microclimates, different air quality and urbanization characteristics between Mashhad and Torbat Heydariyeh.

In this research, anomalies were used to detect mutations. Firstly, the anomalies of each variable for each day of each year were calculated based on Equation (8). Then, the decadal average was calculated. Finally, the anomaly values were plotted in three decades. It should be noted that in each anomaly diagram, the horizontal axis represents days of a year and the vertical axis represents the decadal averages of anomalies. Figure 3 shows maximum temperature anomalies for selected stations at Mashhad, Sabzevar, and Torbat Heydariyeh during the period of 1980–2009. As an example, at Mashhad station, there is a significant seasonal pattern in the anomaly of maximum temperature which began in the mid-1980s and became even more obvious as decades passed by. Positive anomalies showed an increase while approaching the end of the study period. In the 2000s, it showed positive anomalies almost all year round, which indicates an increase in the maximum temperature.

During the winter season (22 December–21 March), the maximum temperature showed an increase from roughly 1 °C in the 1980s to 3 °C in the 1990s. In the 2000s, this increase was up to 3.6 °C in the early season. It is interesting to note that the warming time in every decade also occurred earlier than the previous decade, which in turn can have an impact on planting date, phenology and crop yield (Bannayan *et al.* 2010; Eyshi Rezaie & Bannayan 2012; Choi *et al.* 2020). The highest positive deviation of the maximum temperature was approximately 3.5 °C on January 1st for the period of 2000–2009. According to the Sabzevar station diagram (Figure 3), the highest increase in winter positive anomalies occurred in the 1990s. The amount of this mutation was approximately 0–3 °C and the maximum amount of this positive anomaly occurred early in the winter (month of January). According to the chart, the winter anomalies trend in the 2000s was positive, however, its increasing rate was less than in the 1990s. The findings of Zarenistanak *et al.* (2014) and Kousari *et al.* (2013) also confirm the beginning of significant trends since the 1990s. The Torbat Heydariyeh station chart showed an irregular increase in the maximum temperature anomaly in the 2000s (Figure 3). The trend started from the beginning of the winter and reached its peak at the end of this season. In the 1980 and 1990s, the maximum temperature deviation was often negative.

Minimum temperature analysis

The MK statistical test results of the minimum temperature series are presented in Table 3. According to this table, the minimum temperature variable for all stations showed an increasing trend during winter at 95% level of confidence. The observed trends were significant in all stations except for Torbat Heydariyeh. According to the obtained values, the warming trend of the Sabzevar station was higher in winter than other stations. Figure 4 shows the annual time series of the minimum temperature trends at Mashhad, Sabzevar and Torbat Heydariyeh stations. According to the diagrams, all of the three stations had a positive trend. Similar results were obtained by Soltani & Soltani (2008), Tabari & Hosseinzadeh (2011a) and Fallah-Ghalhari *et al.* (2019), in which the highest and the lowest trend were found for Mashhad and Torbat Heydariyeh stations, respectively.

According to the minimum temperature anomaly charts (Figure 5), the positive anomaly of Mashhad station increased decade by decade, and in the 2000s there was no negative anomaly for the minimum temperature. The highest positive anomaly of the winter was found to be

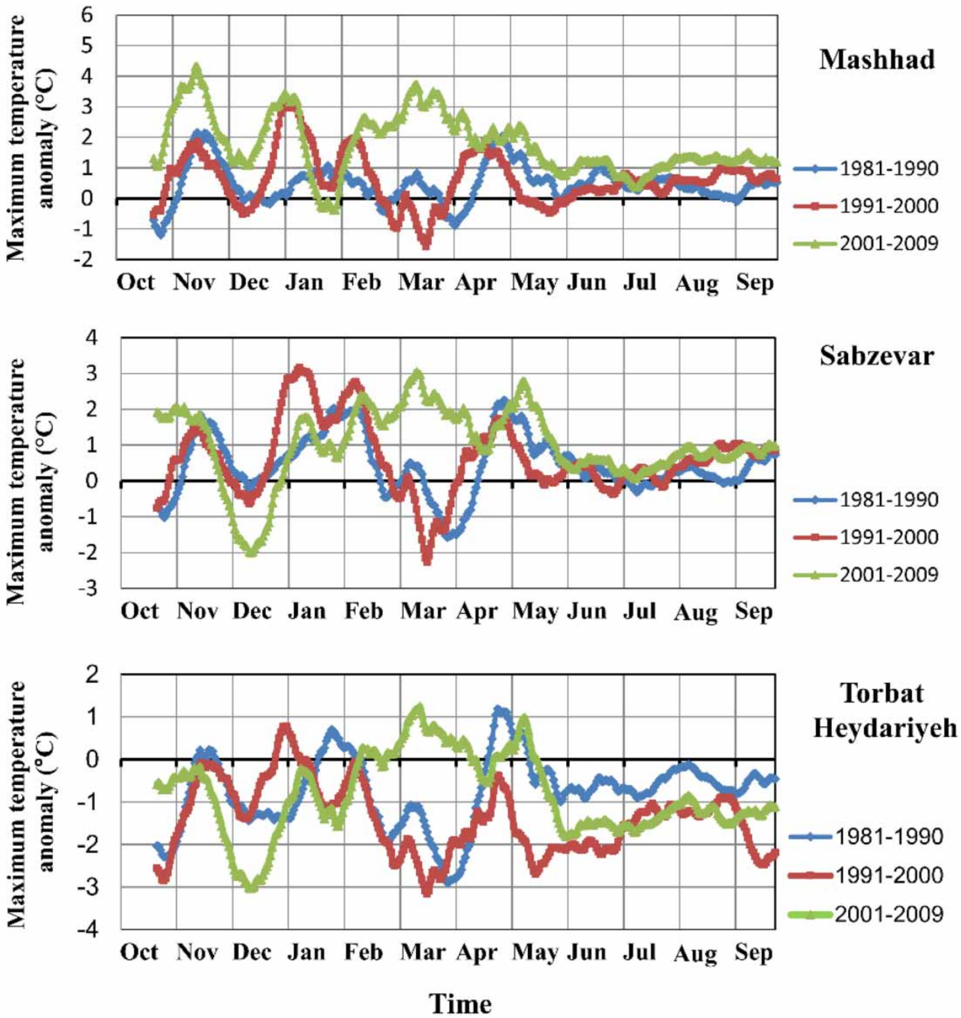

Figure 3 | Monthly and seasonal analysis of maximum temperature anomaly at selected stations.

Table 3 | The Mann–Kendall test results for minimum temperature variable at 95 and 99% confidence levels

T_{min} (°C)	Mashhad	Kashmar	Quchan	Sabzevar	Sarakhs	Torbat Heydariyeh
P-Value	0.002	0.028	0.003	0.000	0.009	0.250
Z-Mk	2.838	1.901	2.690	4.309	2.358	0.672
Trend	* +	* +	* +	* +	* +	0

(+) = Positive trend, (–) = Negative trend, (0) = No significant trend, (*) = Significant level of 95%, (**) = Significant level of 99%.

2.5 °C in the 2000s. However, in general the largest mutation occurred in the 1990s, when its positive anomaly reached from 2 to 2.4 °C. For the rest of the year, a similar trend was observed for all decades.

The Sabzevar station anomaly diagram showed a clear seasonal pattern in the 1990s. As shown in Figure 5 the anomaly of winter months in the 1990s was higher than other decades. The anomaly with a 2 °C rise reached 4.6 °C in the early part of the winter season. Like the Mashhad station, there was no negative anomaly in both decades of 1990 and 2000 at this station. However, the minimum temperature anomaly in the 2000s was less than in the

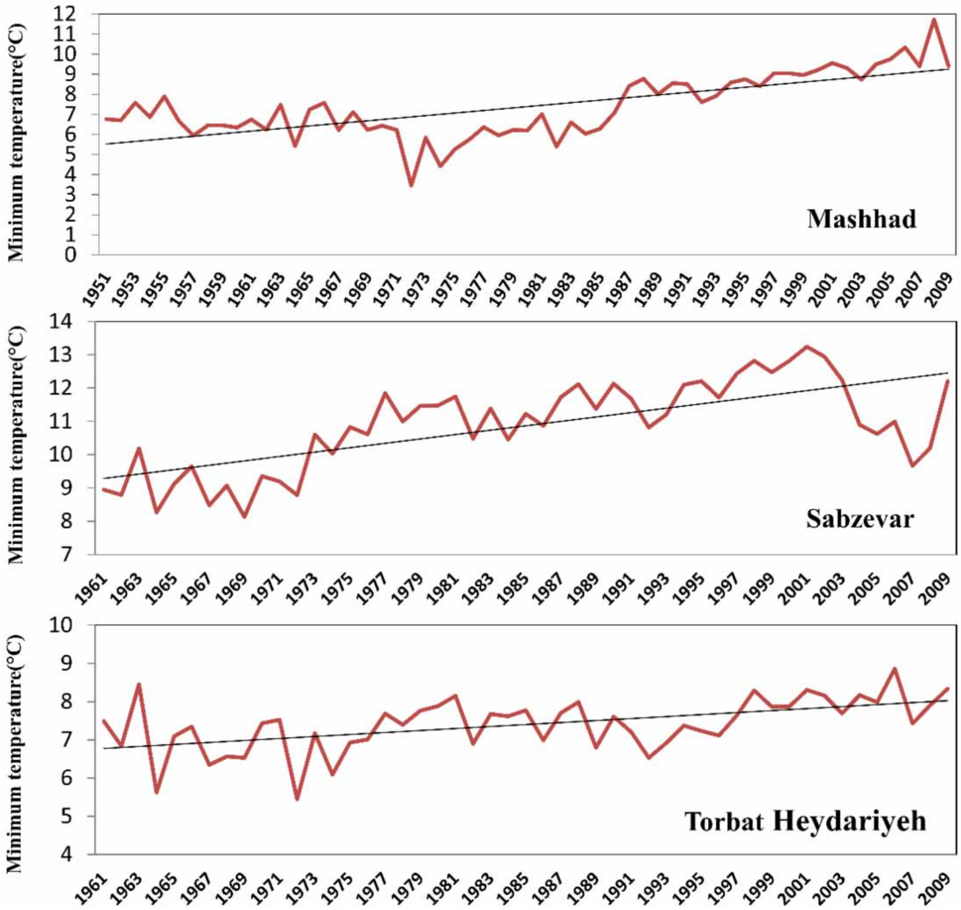

Figure 4 | Time series and linear trends of the minimum annual temperature at selected stations.

1990s and there was not a specific pattern in the seasonal trend of the 2000s. This indicates a general warming of the temperature with a significant increase in minimum temperatures in recent decades. As shown in Figure 5, a clear seasonal pattern was not observed at Torbat Heydariyeh station. Only in the 1980s was there a seasonal mutation from 1 to 1.5 °C in the early winter season, and in other decades there was no significant pattern. The positive anomalies variations were not significant in the studied decades. In addition, the 2000s anomaly was concluded to be positive in most of the months. Generally, it was found that the maximum and minimum temperatures in the seasonal (winter) and annual periods had an increasing trend at most stations. The results were consistent with the findings of Tabari & Hosseinzadeh Talaiee (2011a), Soltani *et al.* (2016) and Fallah-Ghalhari *et al.* (2019). They also concluded that maximum and minimum temperature changes in winter were incremental and more noticeable than in other seasons. Anomaly analysis revealed an increase in the minimum temperatures in January for most stations. Similar to the Tabari & Hosseinzadeh Talaiee (2011a) findings, the monthly minimum temperature trend at Mashhad station was more evident than other stations. The anomaly values of the maximum (Figure 3) and the minimum temperature (Figure 5) were compared, and as can be seen the minimum temperature anomaly variation was more than the maximum's. It is also evident that minimum temperatures and the winter season had a more stable trend. Kousari & Zarch (2011) and Fallah-Ghalhari *et al.* (2019) also concluded that there is a significant increase in the temperature parameters, especially the minimum temperature, in arid and semi-arid regions of Iran. As in this research, Folland *et al.*

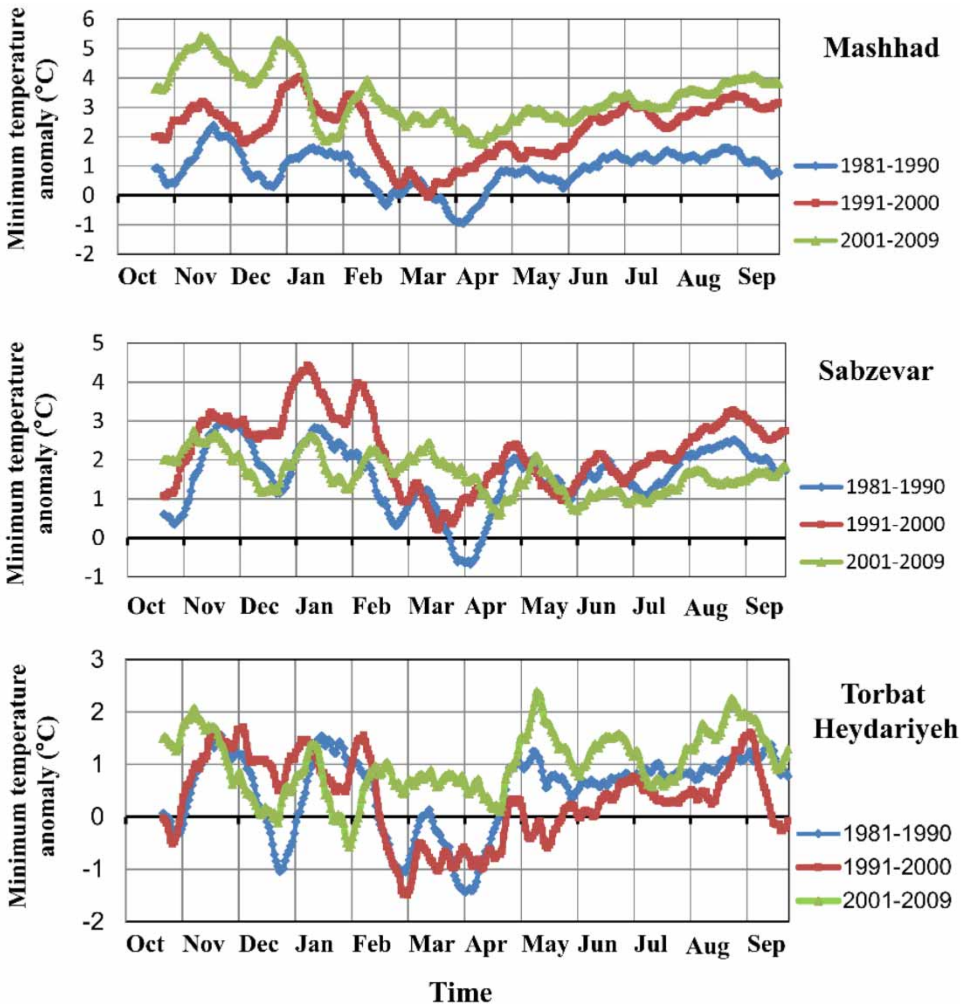

Figure 5 | Analysis of monthly and seasonal minimum temperature anomalies at selected stations.

(2001), Ghasemi (2015) and Khan *et al.* (2019) also reported that the minimum temperature increased more than the maximum temperature on a global scale. The aforesaid results are consistent with the findings on a global scale (Iqbal *et al.* 2016; Vikhamar-Schuler *et al.* 2016; Hillebrand & Proietti 2017; Salman *et al.* 2017; Khan *et al.* 2019; Zhao *et al.* 2020). The results of the maximum and minimum temperature analysis suggest regional strategies for water resources and environmental management in the study area. In particular, according to research by Fallah-Ghalhari *et al.* (2019), indices of warm days and warm nights showed significant positive trends at Mashhad and Sabzevar stations.

Temperature range analysis

Table 4 shows the results of the MK statistical test on the time series of the daily temperature variations range. According to this table, the daily temperature range at Mashhad, Sabzevar and Torbat Heydariyeh stations showed a negative trend. This variable was without trend in the two stations of Kashmar and Quchan. At the Sarakhs station there was a positive trend at the 99% confidence level. Figure 6 shows the linear trend in the annual time series of temperature range. According to this figure, the temperature variation range has decreased in all three selected stations. The decrease in the Torbat Heydariyeh station is

Table 4 | The MK test results for daily temperature range variable at 95 and 99% confidence levels

T_r (°C)	Mashhad	Kashmar	Quchan	Sabzevar	Sarakhs	Torbat Heydariyeh
P-Value	0.015	0.829	0.100	0.060	0.064	0.009
Z-Mk	−2.151	−0.950	1.278	−1.55	1.518	−2.327
Trend	−*	0	0	−**	** +	−*

(+) = Positive trend, (−) = Negative trend, (0) = No significant trend, (*) = Significant level of 95%, (**) = Significant level of 99%.

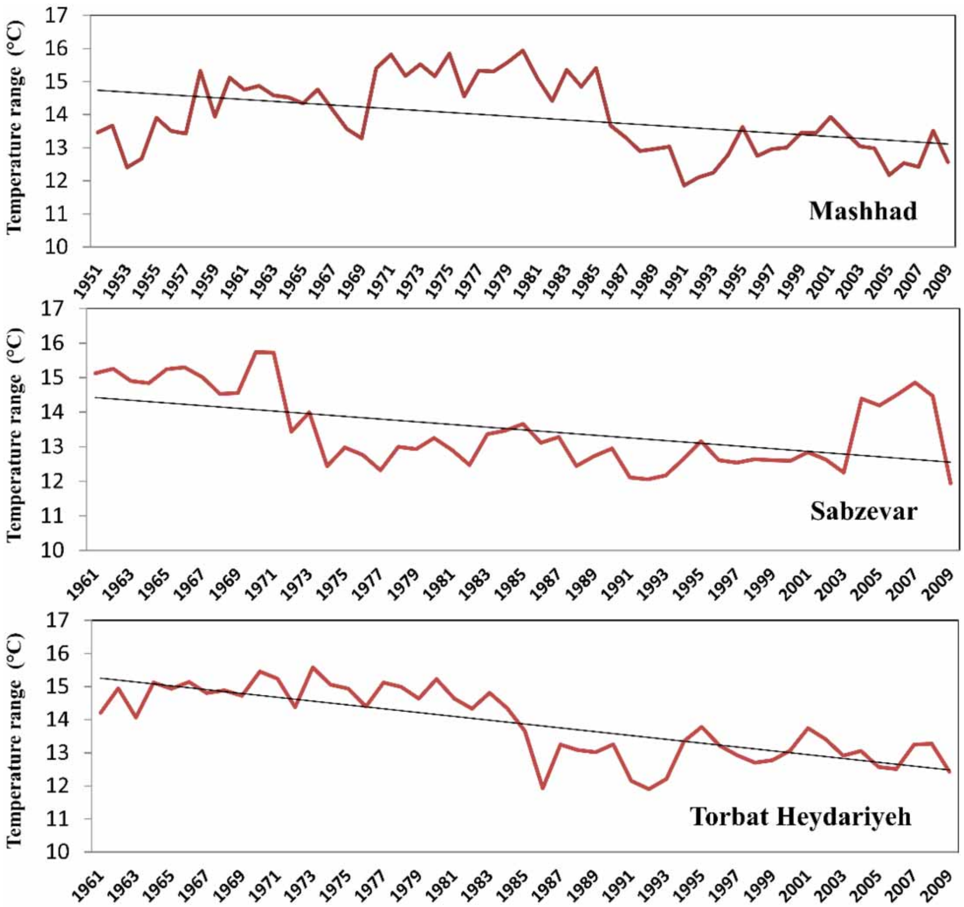

Figure 6 | Time series and linear trends of the daily temperature range at selected stations.

more evident. The results are similar to the outcome of studies by Turkes *et al.* (1996), Rahimzadeh *et al.* (2009), Marofi *et al.* (2012), Nazrul Islam *et al.* (2015), Soltani *et al.* (2016), Salman *et al.* (2017), Khan *et al.* (2019) and Zhao *et al.* (2020) performed in arid areas. The trend in the temperature range means that the range of extreme temperatures (the maximum and minimum temperatures) has changed; however, the amounts of changes are not the same. The decreasing trend of the daily temperature range indicates that the maximum and minimum temperatures are getting close to each other. It seems that significant changes in maximum and minimum temperatures have changed the daily temperature range over time, especially in the winter season. According to the IPCC (2007), the global daily temperature range has decreased by 0.1 °C per decade between 1950 and 1993. However, the trend is highly variable from region to region. As an example, Quintana-Gomez (1999), using the maximum and minimum temperature data of 11 stations in Venezuela and Colombia for the period of 1918–1990, showed that the minimum temperature increased and daily temperature ranges in most stations was reduced. Rahimzadeh & Askari (2004) used the temperature data of 33 synoptic stations in Iran during the period of 1951–1997 in order to study the difference between the changing rates in minimum and maximum temperature and the temperature range. They concluded that the minimum and maximum temperatures were increased at different rates. Furthermore, it was found that the temperature range at Mashhad and Birjand stations showed a decreasing trend.

Figure 7 shows the anomaly of the temperature range at the selected stations. In all three stations the anomalies were often negative in most of the months. This was observed at stations where their minimum temperature anomaly increased more than their maximum temperature anomaly. For example, the amount of temperature range anomalies for the month of January at Mashhad station dropped from −0.99 °C in the 1980s to −2.23 °CC in the 2000s. Obviously, the reduction of temperature range anomaly is another indicator to confirm the occurrence of winter warming. It can also be seen that at Mashhad and Sabzevar stations, the highest negative anomaly was in the early winter of the 2000s (Figure 7). This is consistent with the trends that were observed for maximum and minimum temperatures. Considering these consistencies, which are illustrated in all diagrams, it can be concluded that the warming of the early days of the winter season is more

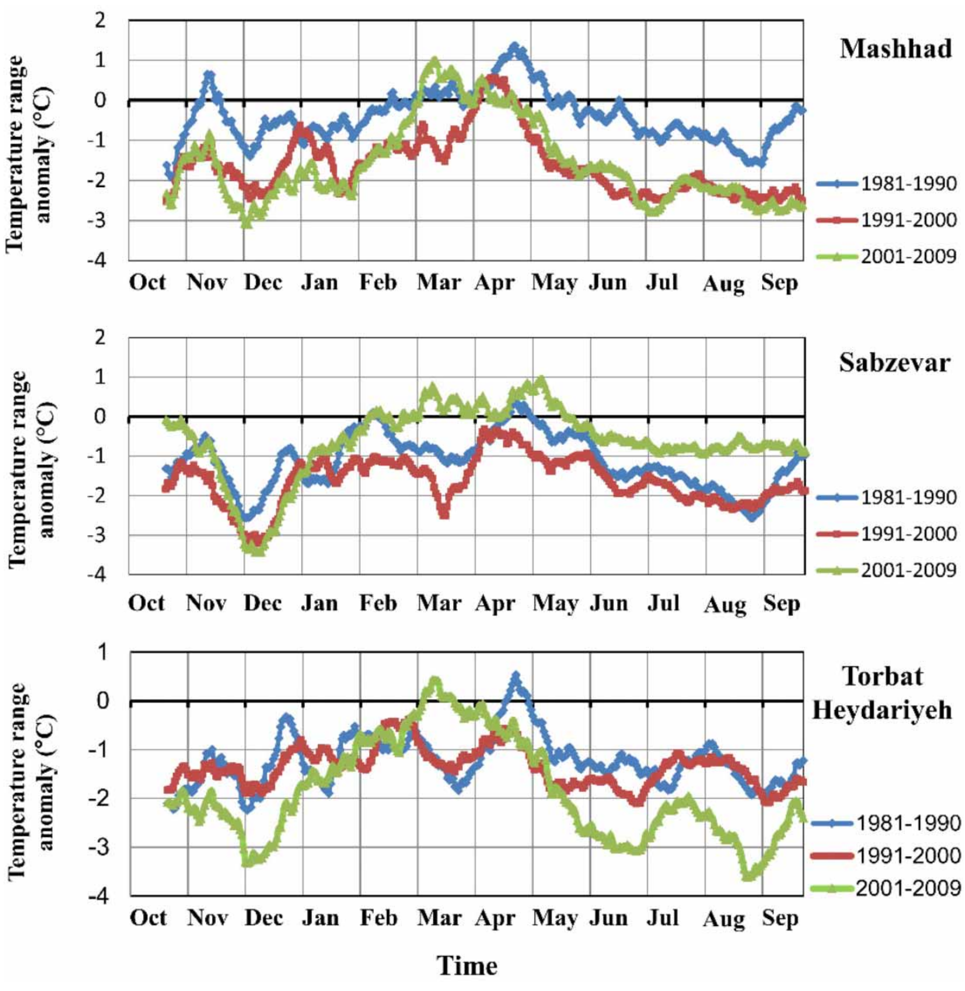

Figure 7 | Monthly and seasonal analysis of the temperature range anomaly at selected stations.

than the mid and late part of this season. Furthermore, the anomaly fluctuations of the 2000s were higher in all three stations than in other decades. The present study showed that the decrease in the daily temperature range anomalies in the selected stations followed the global trend. Since the minimum temperatures increased more as compared to the maximum temperatures, this caused a negative anomaly in the daily temperature range.

Precipitation analysis

The MK test results for the precipitation time series are presented in Table 5. According to the MK statistical values, precipitation showed a significant increase only at Sabzevar station at the 99% confidence level. Although winter precipitation trends in other stations were positive, none of the trends were statistically significant. However, Pour *et al.* (2020) reported that the most significant increase was observed in the central dry and northeast semi-dry regions of Iran in precipitation seasonality for the period 1901–2016. According to a study carried out by Tabari & Hosseinzadeh Talaee (2011b), the precipitation trend in the period of 1966–2003 at Mashhad stations (without trend), Sabzevar (negative trend) and Torbat Heydariyeh (positive trend), was investigated, however, none of the trends were statistically significant. Based on the study performed by Song & Bai (2016), no significant trends were observed for annual precipitation in Central Asia, while precipitation in winter displayed a significant increase (0.11 mm/year) during 1960–2013. Zhao *et al.* (2020) also found a significant increase in precipitation extremes in winter, as compared with spring, summer and autumn for the period of 1960–2016 in an arid and semi -arid region of China.

Time series and linear trends of mean annual precipitation in selected stations are presented in Figure 8. According to the diagrams, precipitation variations at Mashhad and Torbat Heydariyeh stations do not follow a particular trend during different time series. There is also a slight increase in the Sabzevar station, which contradicts the results by Tabari & Hosseinzadeh Talaee's (2011b) research. They reported a negative trend at the Sabzevar station. The length of the time series can be one of the reasons for this discrepancy (Ghahraman & Taghvaeian 2008). These results matched the research outcome carried out by Raziei (2008), Shifteh Sorne'e *et al.* (2012) and Soltani *et al.* (2016). However, based on Pour *et al.* (2020), natural fluctuations of climate may be the cause of many observed precipitation trends in the studies.

In addition to the investigation performed on the annual precipitation, anomalies per decade from 1981 to 2009 in the monthly scale are also presented in Figure 9 for the selected stations. According to the Mashhad station diagram, in most months of the 1980s and 1990s, the precipitation anomalies were often higher than the average. This is more evident in the winter months. It is evident that the highest amounts of positive anomalies occurred in the 1990s. On the contrary, in the 2000s precipitation anomalies were often negative and less than the average values, while in the late spring and summer months, the precipitation anomaly had little variation around the mean. This can be due to the low number of rainy days during spring and summer in the region. The pattern for Sabzevar and Mashhad stations was found to be similar. The highest positive anomaly occurred in late February in the 1980s and 1990s. However, the anomaly was found to be negative for most of the months of the 2000s. Torbat Heydariyeh station showed a different pattern compared to other stations in terms of precipitation anomalies. In the 1980s, negative anomalies occurred in the first months of winter and spring and the maximum positive anomalies occurred in February. Also, most months of the year, even the summer months, showed a negative anomaly in the 1990s. In the

Table 5 | The MK test results for precipitation variable at 95 and 99% confidence levels

P (mm)	Mashhad	Kashmar	Quchan	Sabzevar	Sarakhs	Torbat Heydariyeh
P-Value	0.168	0.139	0.268	0.059	0.131	0.258
Z-Mk	0.961	1.082	0.617	1.560	1.121	0.646
Trend	0	0	0	+**	0	0

(+) = Positive trend, (–) = Negative trend, (0) = No significant trend, (*) = Significant level of 95%, (**) = Significant level of 99%.

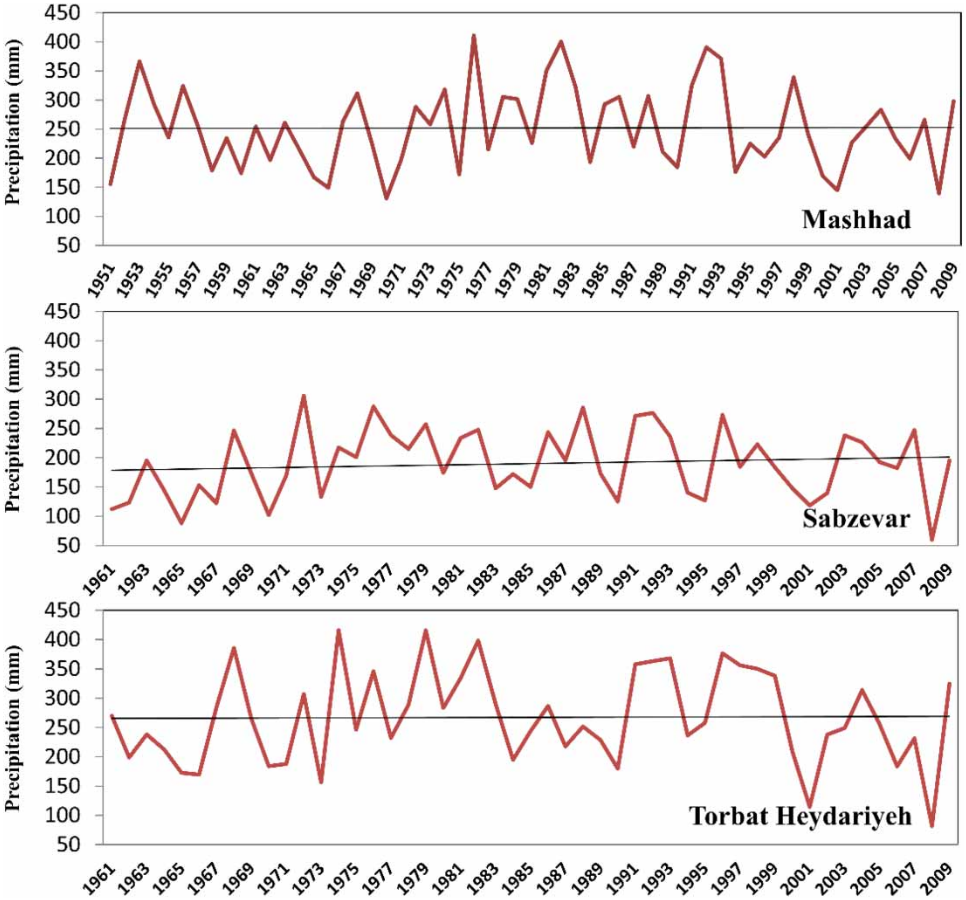

Figure 8 | Time series and linear trends of the mean annual precipitation at selected stations.

2000s, the maximum negative rainfall anomalies were in the winter months. The anomalies of other months were also negative or fluctuated around the mean value. Analyzing the precipitation anomalies showed that there exists a mutation in winter precipitation anomalies. Change in precipitation amount or its distribution in the winter season is a very important factor in rainfed crop production in the study area. Based on Bannayan *et al.*'s (2010) conclusions, the timing of precipitation occurrence could affect the yields of two major crops (wheat and barley) in the drier areas of the region, especially towards the end of the winter months. It is worth noting that the production of these crops determines a major seasonal income for a large portion of farmers living in the northeast part of Iran. Comparison of precipitation anomalies with maximum and minimum temperature anomalies related to Mashhad and Sabzevar stations showed that there was a positive correlation between the two anomalies in the 1980s and 1990s. The fact was most evident in the winter months. In addition, the precipitation anomaly variations occurred later than temperature change. This can be due to the natural differences and complexity of the precipitation. The effects of mountainous region and small-scale processes could also be the reason for the delay. The latter result is also confirmed by Shifteh Some'e *et al.* (2012). In all months of the summer season, none of the studied stations had a significant pattern.

Average temperature analysis

The results of the MK test on the average temperature variable are presented in Table 6. In this case, similar to the minimum temperature analysis (Table 3), the winter average temperature was increasing at all stations except for Torbat

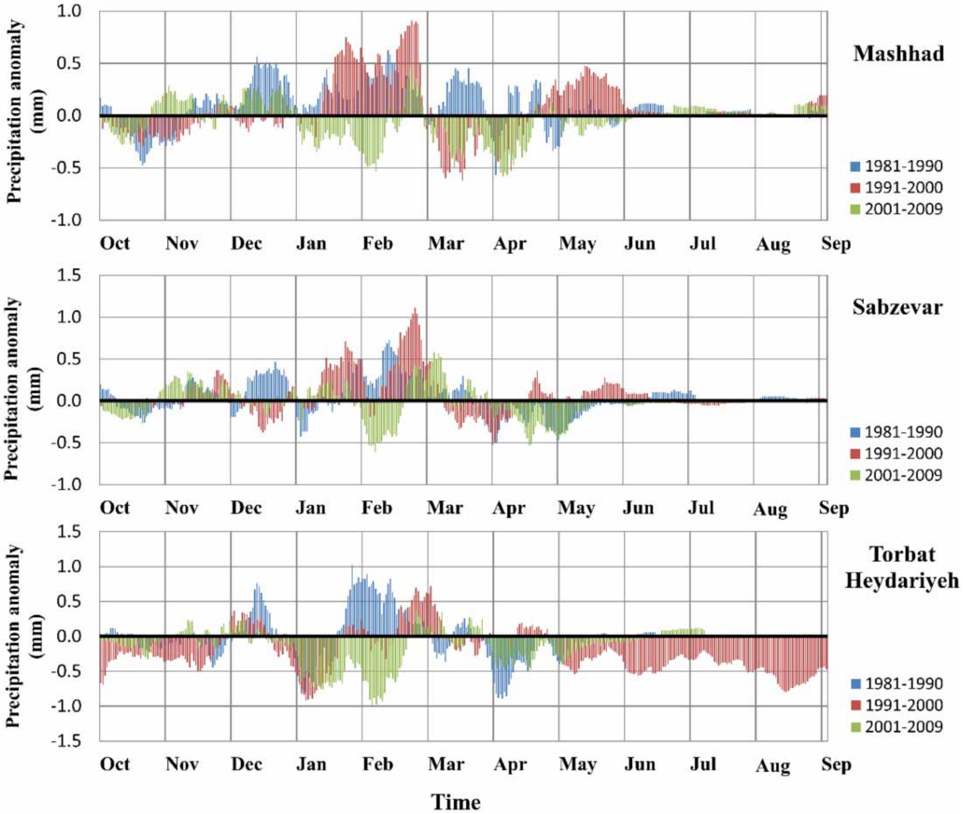

Figure 9 | Monthly and seasonal analysis of precipitation anomalies at selected stations.

Table 6 | The MK test results for average temperature variable at 95 and 99% confidence levels

T_a (°C)	Mashhad	Kashmar	Quchan	Sabzevar	Sarakhs	Torbat Heydariyeh
P-Value	0.019	0.025	0.008	0.001	0.003	0.378
Z-Mk	2.066	1.950	2.380	3.042	2.732	–0.310
Trend	+*	+*	+*	+*	+*	0

(+) = Positive trend, (–) = Negative trend, (0) = No significant trend, (*) = Significant level of 95%, (**) = Significant level of 99%.

Heydariyeh (Table 6). The average temperature linear trend also showed that there is not a significant trend in the annual time scale for this station (Figure 10).

The average temperature anomaly for Mashhad, Sabzevar and Torbat Heydariyeh stations is shown in Figure 11. As can be seen, the average temperature anomalies exhibited a similar pattern with a maximum temperature anomaly (Figure 3) and its difference was in the values of anomaly in different months. For example, the highest positive anomaly of the average temperature (Figure 11) and the maximum temperature (Figure 3) at Mashhad station in the winter season was 4.2 and 3.2 °C, respectively. Likewise, the highest positive anomaly of the average temperature at Sabzevar station was 3.8 °C and the highest maximum temperature anomaly of this station was 3 °C. This shows that the average temperature compared to maximum temperature had more changes in winter. Chung & Yoon (2000) and Zhao *et al.* (2020) also showed that the temperature increased in winter more than any other time of the year. In addition, it was reported that the warming trend

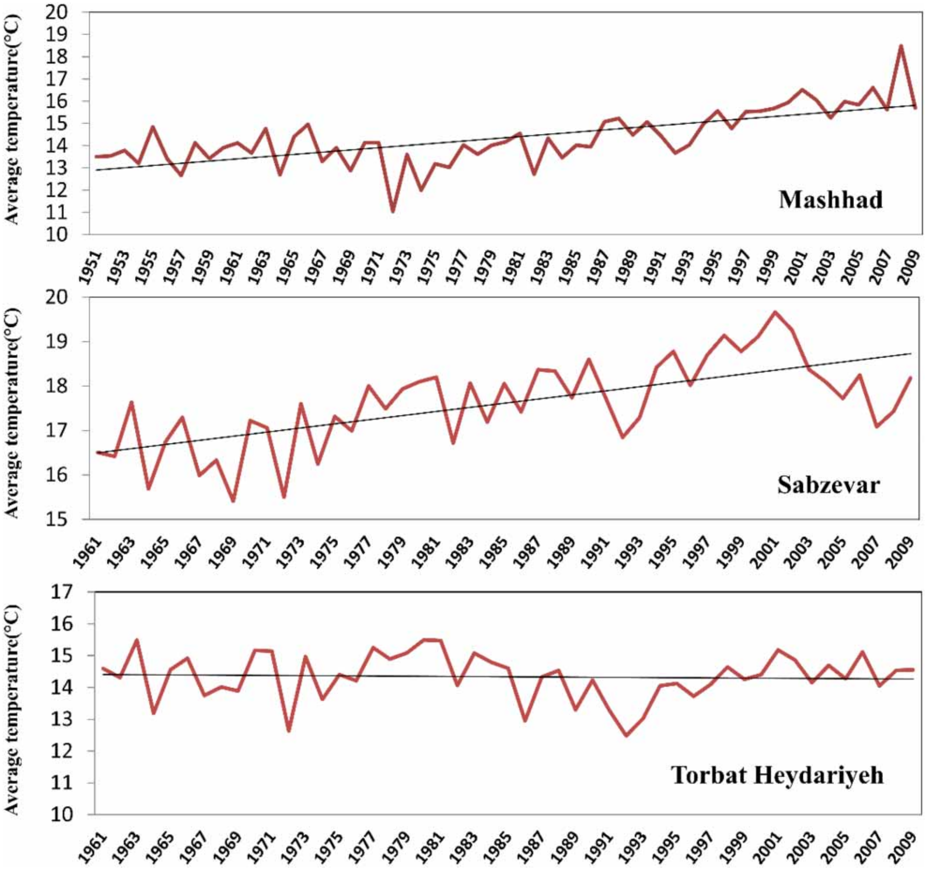

Figure 10 | Time series and linear trends of the average temperature at selected stations.

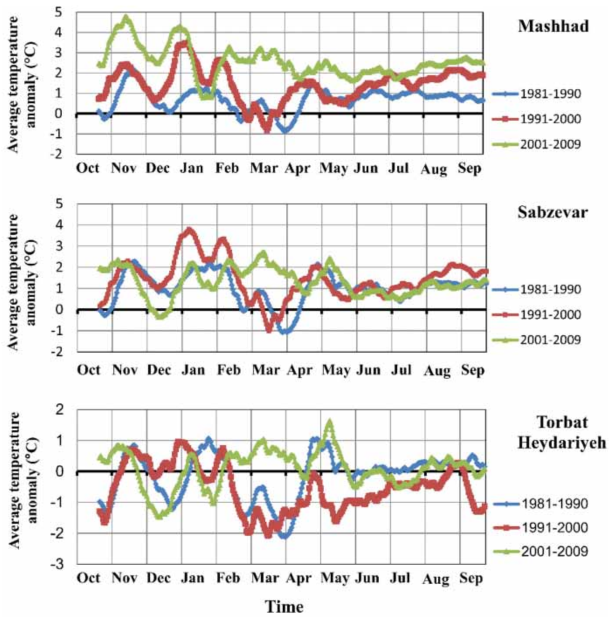

Figure 11 | Monthly and seasonal analysis of average temperature anomalies at selected stations.

in the middle latitudes of Asia with an arid and semi-arid climate (as in many parts of Iran) in the months of November–March (cold seasons) with an increase of 2.4 °C was more than the rest of the year (IPCC 2014).

Overall look on anomalies

Table 7 shows the anomalies in the 1990s and 2000s for each variable and the studied stations. In this table both winter and annual average anomalies are reported. For further investigation, the difference in anomalies in the mentioned decades (denoted by D in the table) has been calculated and presented for each time scale separately. A positive sign indicates that an increase in the anomaly of the 2000s has occurred compared to the 1990s, and a negative sign indicates a decrease. Overall, according to the absolute values of D, in most stations and for most parameters, winter anomalies have increased significantly

Table 7 | Mean anomaly values of the variables in 1990s and 2000s at winter and annual time scale

Station	Time scale	Decade	ΔT_{max}	ΔT_{min}	ΔT_a	ΔP	ΔT_r
Mashhad	Winter	1990–2000	0.38	1.65	1.01	0.22	–1.27
		2001–2009	2.07	2.76	2.42	–0.10	–0.69
		D	+1.69	+1.12	+1.41	–0.32	+0.58
	Annual	1990–2000	0.57	2.27	1.42	0.06	–1.70
		2001–2009	1.76	3.38	2.57	–0.04	–1.62
		D	+1.19	+1.10	+1.15	–0.10	+0.08
Sabzevar	Winter	1990–2000	0.62	2.06	1.34	0.28	–1.44
		2001–2009	1.91	1.94	1.93	0.07	–0.04
		D	+1.29	–0.12	+0.59	–0.21	+1.41
	Annual	1990–2000	0.58	2.24	1.41	0.06	–1.65
		2001–2009	1.05	1.65	1.35	–0.02	–0.60
		D	+0.47	–0.58	–0.06	–0.08	+1.05
Torbat Heydariyeh	Winter	1990–2000	–1.57	–0.06	–0.81	–0.08	–1.04
		2001–2009	0.03	0.62	0.33	–0.31	–0.59
		D	+1.60	+0.68	+1.14	–0.24	+0.46
	Annual	1990–2000	–1.45	0.33	–0.56	–0.25	–1.40
		2001–2009	–0.82	1.06	0.12	–0.12	–1.88
		D	+0.63	+0.72	+0.67	+0.13	–0.48
Sarakhs	Winter	1990–2000	–0.04	0.43	0.20	0.28	–0.47
		2001–2009	2.00	1.36	1.68	0.22	0.64
		D	+2.03	+0.93	+1.48	–0.06	+1.11
	Annual	1990–2000	–0.20	0.39	0.09	0.11	–0.60
		2001–2009	0.88	1.08	0.98	0.08	–0.19
		D	+1.09	+0.69	+0.89	–0.03	+0.40
Kashmar	Winter	1990–2000	–0.11	0.01	–0.05	0.21	–0.12
		2001–2009	1.33	0.87	1.10	–0.25	0.46
		D	+1.44	+0.86	+1.15	–0.46	+0.57
	Annual	1990–2000	–0.49	–0.30	–0.39	0.12	–0.20
		2001–2009	0.35	0.34	0.34	–0.04	0.01
		D	+0.84	+0.64	+0.74	–0.16	+0.20
Quchan	Winter	1990–2000	0.40	1.01	0.71	–0.60	0.22
		2001–2009	2.33	1.67	2.00	0.07	0.66
		D	+1.92	+0.67	+1.29	+0.67	+0.44
	Annual	1990–2000	–0.06	0.50	0.22	–0.57	0.10
		2001–2009	0.73	0.55	0.64	0.10	0.18
		D	+0.79	+0.05	+0.42	+0.67	+0.07

(D) = Difference between anomaly of 1990s and 2000s.

compared to the annual values. This is another confirmation of the occurrence of winter warming in the study area. The maximum temperature anomaly of the 2000s showed an increase at all stations as compared to the 1990s, both on the winter and annual time scale. In addition, in all stations except for Sabzevar, the value of *D* was found to be positive for the minimum temperature and the average temperature. Lorenz *et al.* (2019) also showed that days with extreme heat have doubled for the period of 1996–2018 across Europe. The precipitation anomaly of the 2000s has only increased at Quchan station compared to the 1990s. The reason for this could be the fact that the Quchan station is located at higher latitudes and the climate of this area is significantly wetter than other stations. As the temperature increases, the ability of the atmosphere to retain moisture increases. At the same time, the height of the station (1,270 m) and the topography could also be influential. Torbat Heydariyeh showed different behavior among the studied stations in temperature variables. The anomaly fluctuations at this station were less than the others. This could be due to the height of the station

(1,451 m). According to Pepin & Lundquist (2008), there is more closeness between the temperature and the free atmosphere at higher altitudes; therefore, their trends showed a reduced anomaly in magnitudes. On the contrary, the temperature trend of the stations which are located in the valleys (Figure 1) does not follow a simple pattern, since the local climate depends on how much the energy exchange is facilitated by the combination of topography and the local synoptic conditions (Pepin & Lundquist 2008).

CONCLUSIONS

This study was performed to detect the phenomenon of winter warming in arid and semi-arid areas. In this regard, five variables including daily maximum, minimum and average temperature, precipitation and daily temperature range were investigated using anomalies and the MK test at 95 and 99% confidence levels in the northeast of Iran. Based on the linear trend of the annual time series and according to the global pattern detected by the mentioned studies, the magnitude of the minimum temperature increase was almost twice the maximum temperature in the study area. However, precipitation did not show a significant trend. The results of the MK test showed that there was a significant increase in winter season maximum, minimum and average temperatures for all stations except for Torbat Heydariyeh. Among the studied stations, only Sabzevar station had an increasing trend of precipitation at 99% confidence level.

Winter temperature anomalies (December 22–March 21) at all studied meteorological stations increased more than the annual temperature. A clear reason for this difference is the absence of trends in the anomaly of the summer and autumn (April–December). In all of the studied meteorological stations, an increase in temperature was observed from January to February in the 1990s and 2000s, in which the highest increase in minimum temperature anomaly was greater than the highest increases in maximum and average temperature anomalies. According to the temperature range anomalies, the winter temperature positive changes occurred on almost the same days of the season after the 1990s in all stations. Considering the consistencies which are illustrated in all diagrams, it can be concluded that the warming of the early days of the winter season is more than the mid and late part of this season. Although precipitation trends were not significant on an annual scale, precipitation anomalies increased or decreased in winter as compared to the rest of the year. In addition, it was found that precipitation anomaly variations occurred later than temperature changes in the area.

Overall, according to the results it can be concluded that winter warming occurred in the area. Furthermore, given that many findings in different regions of the world are similar to those of the present study, a larger global change may have occurred and the reason for the detected winter warming could be related to a global phenomenon and not just to the local synoptic climatology. Given the fact that the occurrence and magnitude of winter warming change varied over the decades, its effects could overwhelm various agricultural and environmental activities. Therefore, an investigation of the winter warming impacts on different agricultural, water resources and environmental aspects is suggested. Also, to further address the issues raised in this research, other variables trend must be considered in future studies.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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