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Changes in precipitation characteristics in Iran

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Abstract. Changes in precipitation characteristics in Iran and their relationship with global mean surface temperature (GMST) have not been comprehensively investigated. Therefore, this study analyzed changes in precipitation of different intensities over Iran for the 1987–2017 period. The results show that the total annual precipitation (PRCPTOT) and the number of wet days (RR) have significantly decreased over Iran. Also, the mean precipitation intensity (SDII) has increased somewhat. There is a non-uniform change for three intensity categories of precipitation. The amounts (frequency) of light, moderate and heavy precipitation have significantly decreased at, respectively, 47% (57.9%), 18.7% (15.8%) and 3.94% (7.9%) of stations. Therefore, the decrease in the amount and frequency of light and moderate precipitation is more severe than that of heavy precipitation, and the proportion of heavy precipitation to the total annual precipitation has increased somewhat during 1987–2017. Overall, the result shows that the intensity of decreasing trends in the amount and frequency of precipitation has increased from the south (east) to the north (west) of Iran. Also, SDII has increased from the south (east) to the north (west) of Iran. The sensitivity value was obtained by calculating the ratio of linear trends of precipitation indices and GMST. The regional median sensitivity and percentage change in PRCPTOT, RR, and SDII per 1-kelvin increase in GMST are –6.1%, –11.2% and 12.9% respectively. Considering that Iran is located in the arid subtropical region, a significant decrease in the amount and frequency of precipitation may have destructive effects on water resources.

Key words:
climate change,
classified precipitation,
sensitivity to global warming,
Iran

Introduction

Rainfall and temperature are two important climatic variables that have been widely used to identify climate changes (Yaduvanshi et al. 2021; Yin and Sun 2018). According to the fifth Climate Change Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), "global mean surface temperature (GMST) warmed by 0.85°C between 1880 to 2012" (IPCC 2014). The change in GMST can change rainfall patterns globally (Wang et al. 2016) and influence all characteristics of precipitation in terms of intensity, frequency and duration (Lehner et al. 2006). The sixth report of the IPCC has established that human-induced greenhouse gas emissions have led to an increased frequency and intensity of some weather and climate extremes (Seneviratne et al. 2021). Extreme weather and climate events can lead to severe human and socio-economic losses (Ebi and Bowen 2016; Zhang et al. 2017). Thus, understanding changes in characteristics of climate elements such as temperature and precipitation is significant for society (Li et al. 2022). The past decade has seen many studies devoted to the temporal and spatial characteristics of precipitation over global, continental and regional scales. Recent studies show that heavy precipitation has significantly increased in North America (Easterling 2017; Li et al. 2022), Europe (Myhre et al. 2019), Australia (Herath et al. 2017), South America (Donat et al. 2013), Southeast Asia (Ge et al. 2019), China and India (Yaduvanshi et al. 2022). Sun et al. (2022) studied trends in extreme precipitation over global land areas based on high-quality station data from 1900–2018 and reported that extreme precipitation had increased at about two thirds of stations. They found that extreme precipitation has a statistically significant connection to the GMST.

While annual total precipitation (PRCPTOT) and especially extreme precipitation have been reported to increase globally in response to global climate warming (Myhre et al. 2019; Papalexiou and Montanari 2019; Dai et al. 2020; Kirchmeier-Young and Zhang 2020; Dong et al. 2021; Sun et al. 2021), conversely, some results are showing that some regions have experienced a downward trend. The decreasing trend in rainfall has been observed over the subtropics, Middle East, Mediterranean area, southern Asia, Sahel and western and northern Africa (Trenberth et al. 2007; Longobardi and Villani 2010; Trenberth 2011; Caloiero et al. 2018; Mathbout et al. 2018; Nicholson et al. 2018; Tuel et al. 2020). For instance, Mathbout et al. (2018) have shown a significant decreasing trend in extreme and heavy precipitation events over the eastern Mediterranean and, in the southern parts, a significant decrease in total precipitation. More recently, Acar and Gönençgil (2022) have detected significant decreasing trends in the number of extremely wet and very wet days in most stations over Turkey.

Iran, a mountainous and arid country in south-west Asia is located in the subtropical region. Rainfall over Iran is highly variable in both space and time. More than half of the country receives less than 200 mm, and some parts get less than 50 mm annually (Alijani et al. 2008). Precipitation is scarce in Iran and is expected to be severely affected by future warming; thus, the assessment of change in precipitation is important for sustainable management of water resources and for mitigating damage to society and the environment. The variability of precipitation over space and time may produce environmental disasters, including droughts and floods. According to a Red Cross report “Heavy rains and flash floods have affected more than 2000 cities and towns across almost all of Iran’s 31 provinces” (Yadollahi 2019). The increase in dry periods corresponds well with the increases in the extremely hot temperatures in Iran (Ashraf Vaghefi et al. 2019). Sadeghinia et al. (2022b) showed that the stations located at low altitudes have experienced stronger warming trends than the high region over Iran. In recent years, many researchers have considered the precipitation trends in Iran. In general, a decreasing trend in precipitation has been observed in Iran (Khalili et al. 2016; Javari et al. 2016; Daneshvar et al. 2019; Sharifi and Mir Karim 2020). Also, the number of wet days (RR) has decreased in most stations in Iran (Alavinia and Zarei 2020; Doostan 2020; Sadeghinia et al. 2022a). It is important to ask whether the previous results regarding daily rainfall change patterns in Iran still hold according to additional observations; and the more important question is which of the types of precipitation events in Iran has changed significantly: light, moderate or heavy events? More recently, Wu (2015) and Li et al. (2022) divided all daily precipitation events in the United States into three categories (light, moderate and heavy events) based on the 75th and 95th percentiles of all precipitation events during the study period. Based on Yuan et al. (2017), rainfall classification can be helpful for a more detailed analysis of the precipitation structure (Yuan et al. 2017). Therefore, the method above was used for a more detailed analysis of the precipitation structure in Iran.

In this study, our main objective is to investigate the changes in the amount, frequency and intensity of precipitation in Iran during 1987–2017. Before examining the trends, the rainfall data were first divided into three groups of light, medium and heavy based on the 75th and 95% percentiles, and then the changes in each group were examined. Specifically, we determine (I) the presence of temporal trends in 13 precipitation indices; and (II) the relationship between precipitation of different intensities and GMST to determine the influence of global warming on precipitation of different intensities in Iran. Hence, this article is arranged as follows: Section 2 describes the data and methods. Section 3 describes the results, and Section 4 shows the discussion and conclusions.

Data and methods

Study area

Iran has a total area of 1.648 million km^2 and is located in south-west Asia, between 25°N and 40°N and 44°E and 63°E (Fig. 1). The altitude of Iran ranges between –56 and 5,415 m above sea level (Darand 2020). The climate of Iran is arid and semi-arid (Javari 2016). The mean annual rainfall in Iran is around 250 mm but ranges from less than 100 mm in the east to more than 2000 mm in the north (Kaboli et al. 2021). Most of the precipitation in Iran falls during the winter and autumn seasons due to the prevalence of rain-bearing winds of Mediterranean origin (Raziei et al. 2008). The average annual temperature is about 14°C, with the highest (25°C) in the south and the lowest (6°C) in the north-west (Darand 2020).

Iran has climatological diversity, with three types of climate: 1) dry and semi-dry climate in large parts of internal lands and southern border of Iran; 2) mountainous climate, which itself is subdivided into two categories of cold and moderate mountainous climate; and 3) Caspian climate in a small, narrow area between the Caspian Sea and Alborz Mountain Belt with 600–2000 mm annual rain. Based on the Köppen–Geiger climate classification, 33.5% of Iran is covered by a dry climate and 44.6% by a semi-arid climate (Raziei 2022).

Data

The meteorological data used in this paper are from the Iran Meteorological Organization (IMO). The data have been quality-controlled by IMO. The daily rainfall dataset is available at 400 stations in Iran, but the length of time series at most stations is less than 30 years. We used synoptic stations with no missing data and more than 30 years of data. In total, it contains observations from 74 stations with more than 30 years during 1987–2017. In this study, homogenization of the daily rainfall dataset was assessed using the PMFred algorithm, and linear trend estimates were also obtained using this algorithm (Wang et al. 2010; Rafati and Karimi 2018). The locations of the stations are shown in Figure 1. The altitude of the stations is between –26 and 2,285 m above sea level. The density of the stations was significantly higher in western Iran than in eastern Iran. Data were lacking for central Iran.

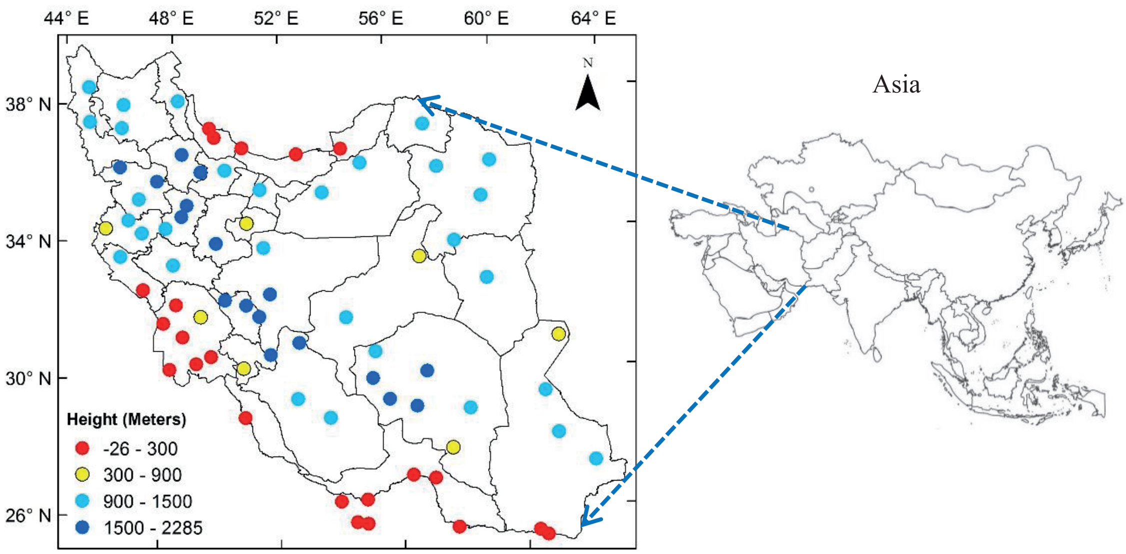

Fig. 1. Location map of stations with continuous daily records of precipitation over Iran, 1987–2017

Precipitation indices

To detect the changes in precipitation, 13 indices were used in this study. Four indices defined by ETCCDI were analyzed, including annual total precipitation (PRCPTOT), number of wet days (RR), simple daily intensity index (SDII), and max 1-day precipitation amount (Rx1day). The nine other indices that were used in this study have been proposed by Li et al. (2022) to describe the characteristics of different intensity categories of precipitation. To extract these indicators, we use different percentiles as thresholds to define precipitation events of different intensities. Based on the 75th and 95th percentiles of precipitation on wet days in the study period, all daily precipitation events are categorized into three precipitations: light, moderate and heavy. For each category, the amount is calculated as the sum of precipitation from events that fall in its corresponding category, and frequency is calculated as the number of days with precipitation that falls within the category in each year. The amounts in each category are divided by annual total precipitation to estimate the contributions due to different intensities of precipitation (Li et al. 2022). All indices are presented in Table 1.

Methods

In this study, several well-established methodologies that were employed by Li et al. (2022) were used. These include estimation of the long-term trend in precipitation indices using the non-parametric Mann–Kendall (MK) and Sen's slope, and quantification of the relationship between precipitation indices and global mean surface temperature (GMST) by fitting least-squares regression to the precipitation indices with GMST as a covariate. The GMST data were downloaded from the website of the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) (Hansen et al. 2010). The GMST is expressed as temperature anomalies relative to 1951–1980. Field significance for the study area is established using the bootstrap method of Livezey and Chen (1983). The details of this method were presented in Westra (2013) and Sun (2021). The methods used are briefly summarized below.

First, the M–K test is employed to detect the trends in precipitation indices (Kendall 1976). The M–K test has been applied frequently in analyzing environmental data (Mathbout et al. 2018; Ma et al. 2021; Sun et al. 2021; Li et al. 2022); since it is not influenced by the data

Table 1. Precipitation indices used in this study

Index	Description	Unit
PRCPTOT	Annual total precipitation (≥1 mm/day)	mm
RR	Number of wet days (≥1 mm/day)	day
SDII	Simple daily intensity index (SDII), which is the average rainfall rate on "wet days" (R≥1mm), measured in mm/day, during the period of interest (year, season or month)	mm/day
Rx1day	Annual maximum 1-day precipitation	mm
PRCLTOT	Precipitation amounts due to light precipitation days (≤75th percentile of precipitation on wet days in the study period)	mm
PRCLF	Number of light precipitation days	day
PRCLCON	Precipitation contribution due to light precipitation days	%
PRCMTOT	Precipitation amounts due to moderate precipitation days (>75th percentile and ≤95th percentile of precipitation on wet days in the study period)	mm
PRCMF	Number of moderate precipitation days	day
PRCMCON	Precipitation contribution due to moderate precipitation days	%
PRCHTOT	Precipitation amounts due to heavy precipitation days (>95th percentile of precipitation on wet days in the study period)	mm
PRCHF	Number of heavy precipitation days	day
PRCHCON	Precipitation contribution due to heavy precipitation days	%

distribution and is less sensitive to outliers (Hadri 2021). The M–K test statistic S is calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} sgn(x_j - x_i)$$

Where: xi and xj are sequential data for the i-th and j-th terms; n is the sample size; and

$$sgn(x_k - x_j) = \begin{cases} 1, & x_k - x_j > 0 \\ 0, & x_k - x_j = 0 \\ -1, & x_k - x_j < 0 \end{cases}$$

The standard normal test statistic Z_s is computed as:

$$Z_s = \begin{cases} \frac{S-1}{\sqrt{Var(s)}}, & x_k - x_j > 0 \\ 0, & x_k - x_j = 0 \\ \frac{s+1}{\sqrt{var(s)}}, & x_k - x_j < 0 \end{cases}$$

The standard normal variable Z has been used to detect the trend and its significance level. Positive (negative) values of Z show a rising (declining) trend in the time series. The null hypothesis is that there is no monotonic trend in the analyzed time series. The alternative hypothesis is that the trend exists. In this study, the probability value $p<0.05$ was used as the criterion for accepting the alternative hypothesis. The existence of autocorrelation can increase the probability of detecting a significant trend (Bayazit and Önöz 2008). Therefore, a trend-free pre-whitening (TFPW) method was employed to remove serial auto-correlation (Praveen et al. 2020; Jerin et al. 2021). Each station was classified as "significant increasing", "significant decreasing", and "non-significant" trend, using a 5% significance level. After detecting the trend of precipitation indices in each station separately, to evaluate the field significance of trends in a study area, the bootstrap method of Livezey and Chen (1983) was applied. The steps are as follows: (1) the precipitation indices time series for each station are randomly shuffled by year; (2) after each reshuffling, trends are computed and tested for statistical significance by the M–K test; (3) the bootstrap sampling is replicated 1000 times; using 1000 random tests, the desired statistic is computed, which is then used to build a probability distribution for that test statistic; and (4) if the test statistics from the observed data are put outside the 95% probability distribution obtained by resampling, then the test statistics is qualified as field significant at the 5% significance level (Sun et al. 2021; Li et al. 2022). Sen's slope (Sen 1968) is another non-parametric method used for the estimation of the magnitude of the trend in time. Sen's Estimate, coupled with the M–K test, is an effective statistical tool for analyzing time-series meteorological data.

Second, the least-squares regression is used to quantify the relationship between GMST and precipitation indices. A regression analysis spawns an equation to characterize a statistical relationship between a predictor (GMST) and the response variables (precipitation indices), which predicts new observations. We would like to examine whether the distributions of the precipitation indices change with a change in GMST. In this study, the percentage change in precipitation indices per 1 K of GMST increase is estimated and interpreted as an estimate of the sensitivity of different precipitation indices to GMST change. The sensitivity value is attained by calculating the ratio of linear trends of precipitation indices and GMST during 1987–2017. The uncertainty of the sensitivity value is estimated using a bootstrap method. Bootstrap is a method of random sampling with replacement. We select n years (n=50 for the 1987–2017 period) at random with replacement (Li et al. 2022) and calculate the linear trends using the precipitation indices and temperature appropriate to the years selected, which preserves the connections between precipitation indices and temperature. Then, the ratio of linear trends of precipitation indices and GMST is calculated to estimate the sensitivity. Resampling is performed 1000 times to develop a sampling distribution for the sensitivity, which is used to estimate a 5–95% confidence interval for the sensitivity value (Sun et al. 2021).

Result and analysis

Changes in the characteristics of daily precipitation

Figure 2 shows the maps of PRCPTOT, RR, SDII and Rx1day trends during 1987–2017. About 24%, 60%, 2.6% and 0% of stations showed statistically significant decreasing trends in PRCPTOT, RR, SDII and Rx1day, respectively. The significant decreasing trends in PRCPTOT and RR are much higher than what could be expected from random chance alone, as they are far outside of the simulated bootstrap distribution (Fig. 4), but the significant decreasing trends in SDII are comparable with the expectation from random chance and are not field significant (Fig. 5). In contrast, the percentages of stations showing statistically significant increasing trends are only about 0%, 0%, 6.5% and 0% for PRCPTOT, RR, SDII and Rx1day, respectively (Fig. 2). The significant increasing trends in SDII are comparable with the expectation from random chance and are not field significant (Fig. 5). The upward and downward trends in SDII are 67.1% and 32.6%, respectively. This means that many more stations show increasing trends than decreasing trends. Overall, these results indicate that there have been decreasing trends in the amount and frequency of precipitation during 1987–2017 over Iran. In addition, weak increasing trends have occurred in the mean intensity of precipitation over Iran. The Rx1day does not show any significant trend (Fig. 2d).

The spatial distribution of stations with significant decreasing trends in PRCPTOT shows that there is a higher concentration in the north-west, west, north, north-east and south-west of Iran. The weaker decreasing trends in PRCPTOT are observed in the center, southern coast and south-

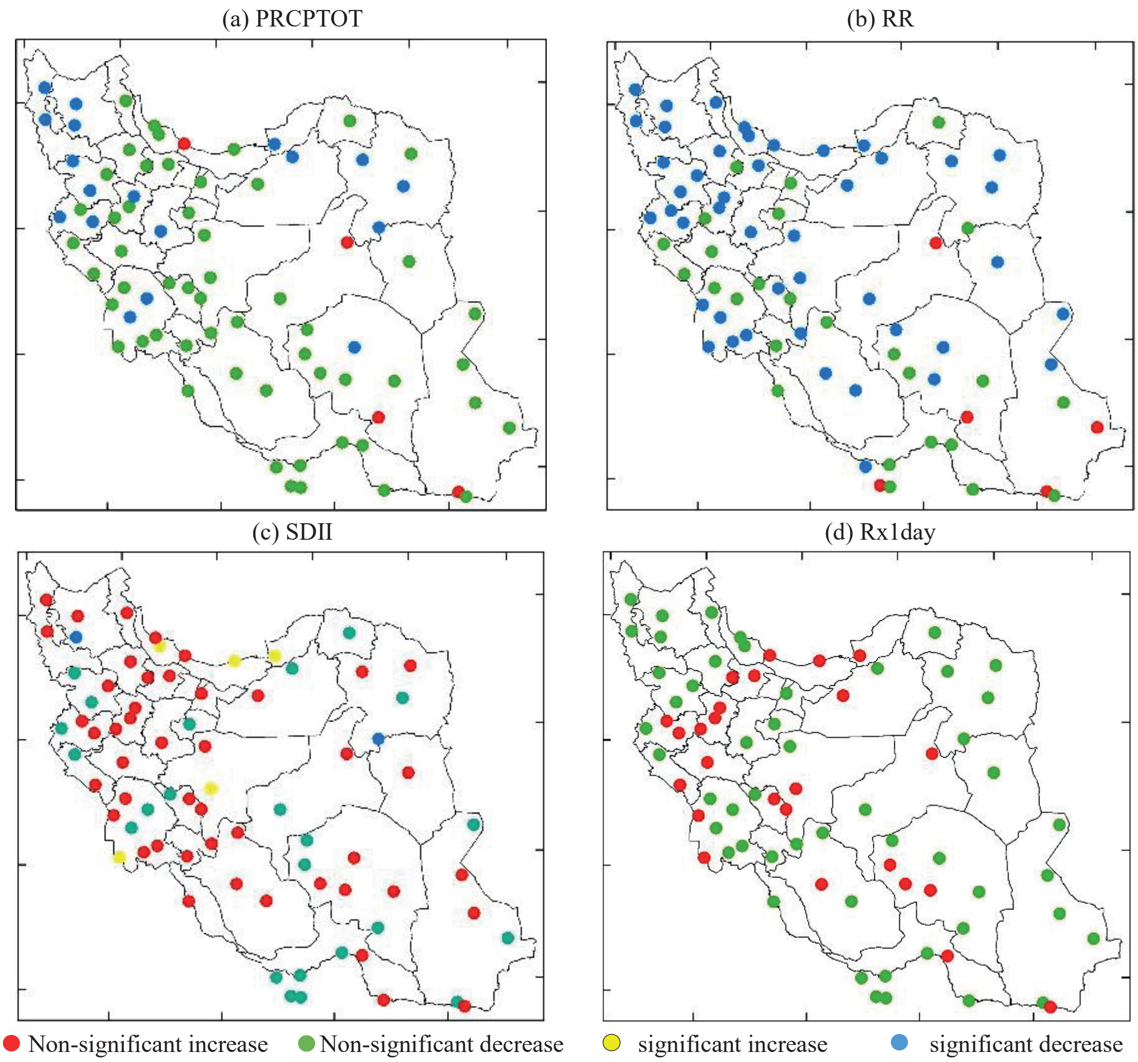

Fig. 2. The analysis of the Mann–Kendall trend for the periods of 1987–2017. (a), (b), (c) and (d) manifest the maps of trends for PRCPTOT, RR, SDII and Rx1day. Red dots show non-significant increasing trends, and green dots indicate non-significant decreasing trends. The two-sided test done at the 5% level indicated that solid blue and yellow dots show significant increases and decreases in the trends.

east of Iran. Figure 2a indicates that no significant negative trend in PRCPTOT is observed below 30°N. On average, declining precipitation trends at rates –3.1, –2.68, –2.26, –2.16, –1.57, –1.33, –0.68 and –0.5mm/year have been observed in the south-west, north-west, west, north, north-east, southern coast, center and south-east of Iran, respectively. In terms of the spatial distribution of the RR, the maximum decreases are observed in the southern coast of the Caspian Sea, north-west, west and north-east of Iran. Overall, most of the stations that have experienced a statistically significant decrease in PRCPTOT and RR are located in the western and northern half of Iran (Fig. 2a, b). Trend spatial analysis of PRCPTOT and RR in Iran shows that the intensity of decreasing trends in the amount and frequency of precipitation increases from south to north and from east to west (Fig. 3a, b). The spatial distribution of SDII, as shown in Fig. 2c, reveals that most of the significant increasing trend is witnessed on the southern coast of the Caspian Sea. On average, precipitation intensity in this area has increased by 0.04 mm/year. Stations that show a non-significant increasing trend in SDII are distributed throughout the study area (particularly over the northern half of Iran). Trend spatial analysis of SDII shows that the intensity of increasing trends increases from south to north and from east to west in Iran (Fig. 3c). According to the obtained results, the precipitation variable has experienced more severe changes in terms of amount, frequency and intensity in the western and northern half of Iran compared to the eastern and southern half (see Fig. 3a, b, c).

Changes in the characteristics of different intensity categories of precipitation

In this section, the change trends for three categories of precipitation will be analyzed. The spatial distribution of change trends in different characteristics (amounts, frequency and contribution to total annual precipitation) of different intensity categories of precipitation, including light, moderate

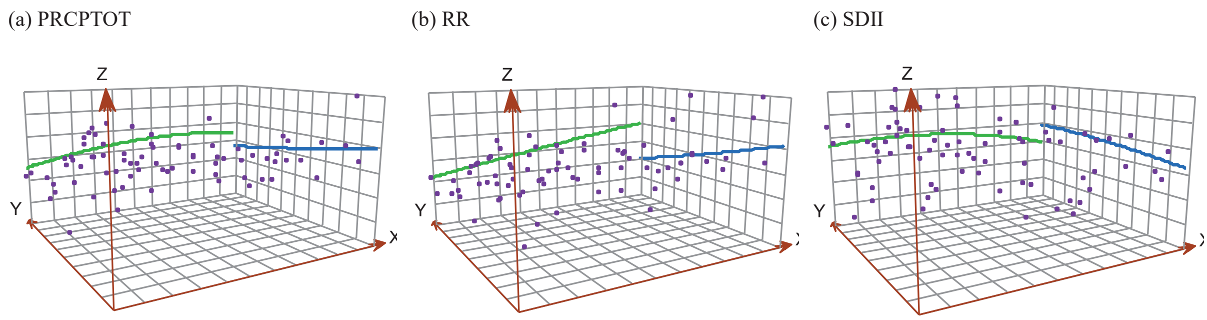

Fig. 3. Trend spatial analysis for (a) PRCPTOT, (b) RR and (c) SDII over Iran. Green and Blue lines represent the west–east and north–south trends, respectively.

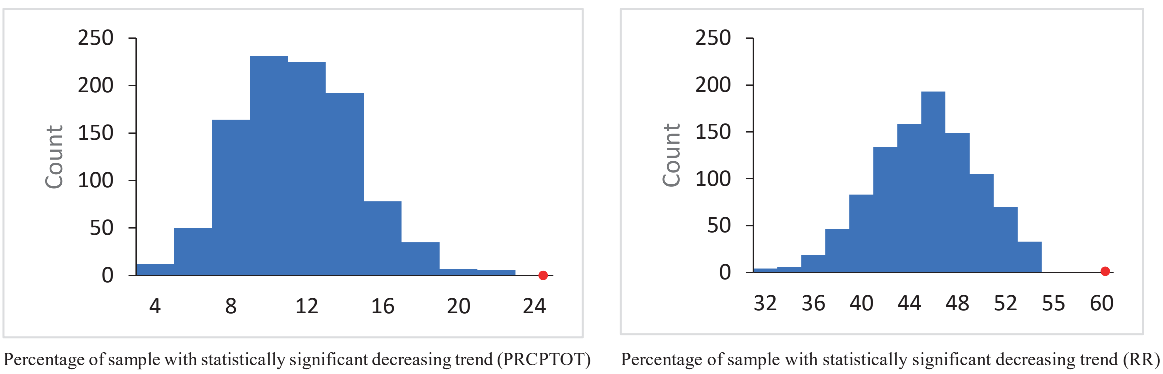

Fig. 4. Percentage of stations indicating statistically significant decrease in the trends based on Mann–Kendall analysis for PRCPTOT (left) and RR (right) indices. The distribution of the results from 1000 bootstrap realizations of the PRCPTOT and RR indices are shown by the histogram. The values from the observed data are represented by red dots.

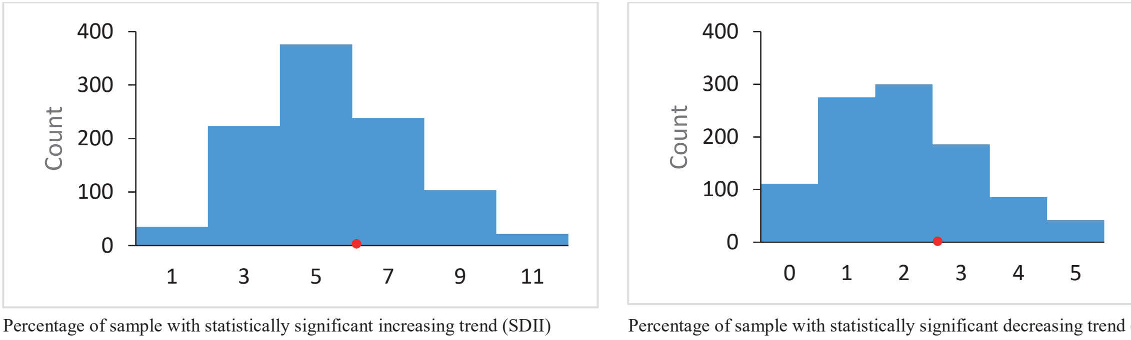

Fig. 5. Percentage of stations indicating statistically significant increase (left) and decrease (right) in the trends based on Mann–Kendall analysis. The distribution of the results from 1000 bootstrap realizations of the SDII indices are shown by the histogram. The values from the observed data are represented by red dots.

and heavy precipitation is demonstrated in Figure 6. The corresponding percentages of stations showing statistically significant change trends are indicated in Figure 7. As is shown in Figure 6a, d and g and Table 2, amount of light, moderate and heavy precipitation have clear decreasing trends in most of the stations. About 47.4%, 18.7% and 3.94% of stations show a statistically significant decreasing trend in the amount of light, moderate and heavy precipitation, respectively. The percentage of stations with significant decreasing trends for the amount of light and moderate categories have field significance, while the decreasing trends of heavy precipitation are not field significant (Fig. 7a). The change trends in the frequency of precipitation in Iran are almost similar to the change trends in the amount of precipitation. In terms of frequency, there is an overall decrease in the frequency of light, moderate and heavy precipitation. About 57.9%, 15.8% and 7.9% of stations show a statistically significant decreasing trend in the frequency of light, moderate and heavy precipitation, respectively. The percentage of stations with significant decreasing trends for the frequency of light and moderate categories have field significance (Fig. 7b), while the decreasing trends of heavy precipitation are not field significant (Fig 7c). Therefore, it can be concluded that the amount and frequency of light and moderate precipitation shows significant decreasing trends, while the amount and frequency of heavy precipitation show no significant decreasing trends in the study area.

Spatially, the significant decreasing trends of the amount and frequency of light precipitation are mostly located in the north, north-west, west and south-west of Iran. On overage, the amount of light precipitation (PRCLTOT) has decreased at rates −1.6, −1, −0.96 and −1.3 mm/year in the north, north-west, west and south-west of Iran, respectively. Therefore, the amount and frequency of light precipitation have decreased more intensely in the western and northern half of Iran compared to the eastern and southern half (Fig. 6a and b). The amount and frequency of moderate precipitation have experienced greater decreases in the north-west, west, south-west and north-east of Iran. On overage, the amount of moderate precipitation (PRCMTOT) has decreased at rates −1, −1.18, −1.56 and −0.52 mm/year in the north-west, west, south-west and north-east of Iran, respectively. Spatially, the changing trends in the amount and frequency for heavy precipitation are very noisy (Fig. 6 G and h). Nevertheless, non-significant downward trends prevail in most sections of Iran. About 65.78% and 60.52% of stations indicate a non-significant decreasing trend in the amount (PRCHTOT) and frequency (PRCHF) of heavy precipitation, respectively (Table 2).

As is shown in Figure 6c, f and i, unlike the amount and frequency trends, the change trends of the contribution to annual total precipitation due to light (PRCLCON), moderate (PRCMCON) and heavy precipitation (PRCHCON) over the space are very noisy. About 2.6%, 7.9% and 3.94% of stations show a statistically significant increasing trend in PRCLCON, PRCMCON and PRCHCON indices, respectively. In contrast, just 2.6%, 3.9% and 0% of stations show a statistically significant decreasing trend in PRCLCON, PRCMCON and PRCHCON indices, respectively. The increasing and decreasing trends are not field-significant. Overall, PRCHCON indices show different change trends from PRCLCON and PRCMCON indices (Fig. 6i). About 57.84% of stations have experienced upward trends in PRCHCON (Table 2). Therefore,

Table 2. Percentages of stations with statistically significant increasing, significant decreasing, non-significant increase and non-significant decrease trends for PRCLTOT, PRCMTOT, PRCHTOT, PRCLF, PRCMF, PRCHF, PRCLCON, PRCMCON and PRCHCON.

Indices	Significant increase	Non-significant increase	Significant decrease	Non-significant decrease	Mean
PRCLTOT	0	7.9%	47.4%	44.7%	-1.72
PRCMTOT	1.3%	17%	18.7%	63%	–0.9
PRCHTOT	1.31%	26.31%	3.94%	65.78%	–0.46
PRCLF	0	6.57%	57.9%	35.53%	–2.21
PRCMF	1.3%	18.4	15.8%	64.5%	–0.87
PRCHF	1.31%	28.94%	7.9%	60.52%	–0.53
PRCLCON	2.6%	40.8%	2.6%	54%	–0.18
PRCMCON	7.9%	39.5%	3.9%	48.7%	0.053
PRCHCON	3.94%	53.9%	0	42.16%	0.015

the proportion of heavy precipitation to the total annual precipitation increased somewhat during 1987–2017 in Iran.

Responses of different indices of precipitation to global warming

First, the regional averages of precipitation indices were calculated at the annual scale for the 1987–2017 period. Then, the Pearson correlation coefficients between precipitation indices and GMST were investigated, and the statistical significance was assessed at the 5% level. The correlations between different precipitation indices and GMST are listed in Table 3. With the exceptions of SDII and Rx1day, all precipitation indices have negative correlations with GMST. The correlation values between PRCPTOT, PRCLTOT, PRCMTOT, PRCHTOT, RR, PRCLF, PRCMF, PRCHF and SDII with GMST are statistically significant at the 99% or 95% confidence level. Other indices (Rx1day, PRCLCON, PRCMCON and PRCHCON) do not show any significant correlations with GMST. Overall, the amount and frequency of precipitation show a significant negative correlation with GMST; conversely, the only negative correlation with GMST was found for SDII. On average, the frequency indices (RR, PRCLF, PRCMF and PRCHF) indicate a stronger correlation with GMST compared to precipitation amount indices (PRCPTOT, PRCLTOT, PRCMTOT and PRCHTOT). Some correlation coefficients between GMST and frequency of precipitation exceed –0.7 (RR and PRCLF).

Figure 8 estimates the regional median sensitivity values of the precipitation of different intensity categories to global warming. Overall, PRCPTOT, the amount of light (PRCLF), moderate (PRCMF) and heavy (PRCHF) precipitation all decrease with global warming, with the median sensitivity values at 6.1% K-1, 5.2% K-1, 5.1% K-1 and 5% K-1, respectively (Fig. 8a). Also, RR, the number of light (PRCLTOT), moderate (PRCMTOT) and heavy (PRCHTOT) precipitation all decrease with global warming, with the median sensitivity values at 11.2% K-1, 5.4% K-1, 5.2% K-1 and 5.3% K-1, respectively (Fig. 8c). Besides, we also compare the responses of mean precipitation intensity (represented by SDII) and the heaviest precipitation events (Rx1day) to warming (Fig. 8b). The regional median sensitivity values are 12.9% K-1 for SDII and 2.8% K-1 for Rx1day, respectively.

Conclusions and discussion

This study investigated changes in precipitation indices in Iran. Based on daily precipitation observations during 1987–2017, daily precipitation was classified into three different categories: light, moderate and heavy precipitation. Then, changes in characteristics (amount, frequency and intensity) of daily precipitation, in terms of both mean precipitation and precipitation events of different intensities (light, moderate, heavy precipitation) and their responses to GMST were analyzed. The main conclusions can be summarized as follows:

1. The total annual precipitation and the number of wet days have both decreased significantly during 1987–2017 in Iran. The percentage of stations with significantly decreasing trends in the total annual precipitation (24%) and the number of wet days (60%) are significantly larger than anything that can be expected by chance for Iran.
2. Although the amount and frequency of light, moderate and heavy precipitation all decreased, the rate of change of the three different categories of precipitation is not the same. The amounts of light, moderate and heavy precipitation significantly decreased at 47%, 18.7% and 3.94% of stations, respectively. Also, the frequency of light, moderate and heavy precipitation

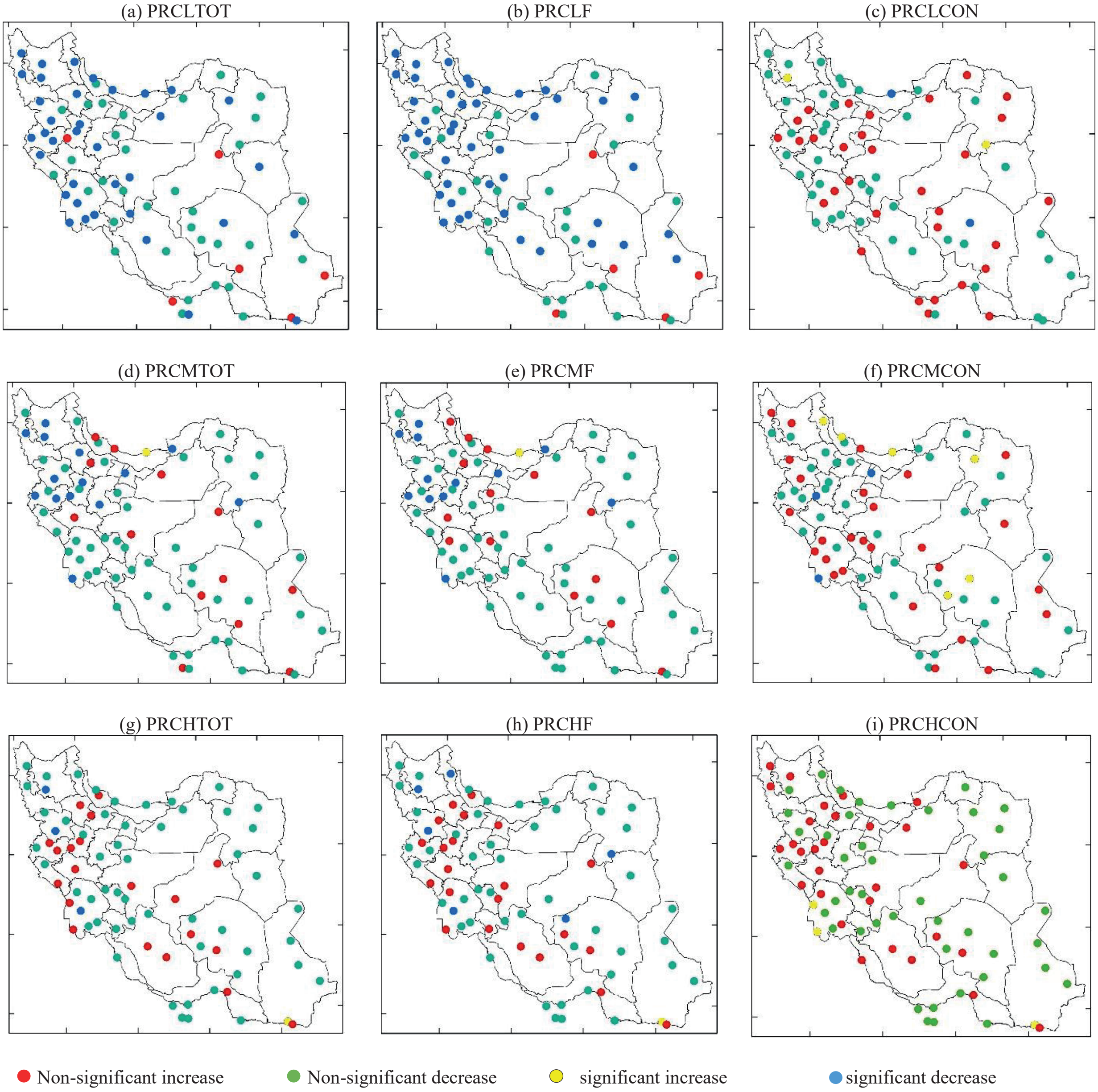

Fig. 6. Mann–Kendall test for characteristics of light, moderate and heavy precipitation during 1987–2017. (a), (d) and (g) show the maps for the amount of light, moderate and heavy precipitation, respectively. Maps of frequency of light, moderate and heavy precipitation are shown by (b), (e) and (h). (c), (f) and (i) indicate maps of the contribution to annual total precipitation derived from light, moderate and heavy precipitation, respectively. Non-significant increasing trends are shown by the red dots and non-significant decreasing trends are shown by the green dots. Solid yellow and blue dots represent statistically significant trends as analyzed by a two-sided test carried out at the 5% level.

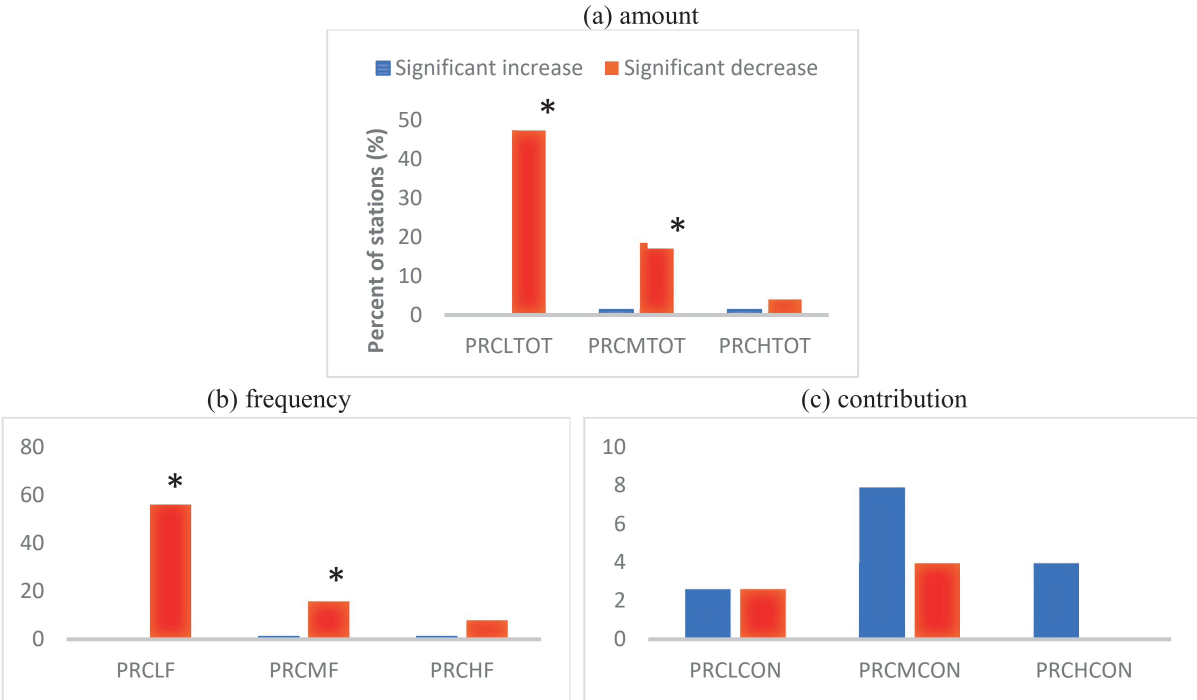

Fig. 7. Percentages of stations with statistically significant increasing and decreasing trends for the light, moderate and heavy precipitation during the 1987–2017 period. (a) indicates the amount of light, moderate and heavy precipitation. (b) shows the frequency of light, moderate and heavy precipitation. (c) represents the contribution to annual total precipitation derived from light, moderate and heavy precipitation. Changes passing the field significantly are shown by the starts.

Table 3. Correlation coefficients between precipitation indices and GMST in the 1987–2017 period

GMST	**PRCPTOT**	**RR**	**SDII**	**Rx1day**	**PRCLF**	**PRCLTOT**	**PRCLCON**
	$\mathbf{-0.53}^{**}$	$\mathbf{-0.71}^{**}$	$\mathbf{0.55}^{**}$	0.14	$\mathbf{-0.73}^{**}$	$\mathbf{-0.68}^{**}$	-0.055
GMST	PRCMF	PRCMTOT	PRCMCON	PRCHF	PRCHTOT	PRCHCON	
	$\mathbf{-0.56}^{**}$	$\mathbf{-0.46}^{**}$	-0.01	$\mathbf{-0.45}^{**}$	$\mathbf{-0.31}^{*}$	-0.17	

**Significant at the 99% confidence level; *Significant at the 95% confidence level

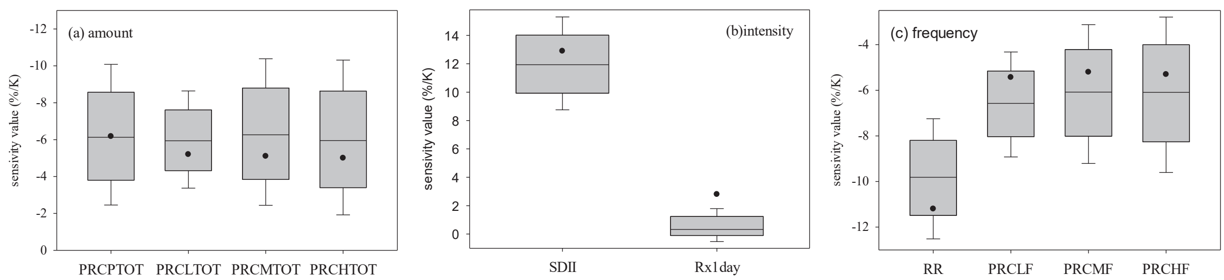

Fig. 8. Regional median sensitivity values of precipitation to increase in GMST for the 1987–2017 period. (a) annual total precipitation, the amount of light, moderate and heavy precipitation. (b) mean precipitation intensity (SDII) and heaviest precipitation event (Rx1day). (c) number of wet days (RR), number of light, moderate and heavy precipitation. The median sensitivities amongst all observing stations over the Iran are indicated by the black dots. The breadth of the distribution from 1000 bootstrap realizations under the null sensitivity hypothesis are summarized by the box-and-whisker plots. In these plots, the center black line marks the median.

significantly decreased at 57.9%, 15.8% and 7.9% of stations, respectively. Therefore, the decrease in the amount and frequency of light and moderate precipitation is more severe than heavy precipitation and the proportion of heavy precipitation to the total annual precipitation increased somewhat during 1987–2017.

3. On average, the intensity of precipitation increased somewhat over Iran. The upward and downward trends in SDII are 67.1% and 32.6%, respectively. This means that many more stations experienced increasing trends than decreasing trends. The Rx1day does not show any significant trend.
4. Trend spatial analysis of PRCPTOT, RR and SDII shows that the precipitation variable experienced more severe changes in terms of amount, frequency and intensity in the western (northern) half of Iran compared to the eastern (southern) half. Overall, the results show that the intensity of decreasing trends of amount and frequency of precipitation increased from the south (east) to the north (west) of Iran. Also, the intensity of increasing trends of SDII increased from the south (east) to the north (west) of Iran.
5. Pearson correlation coefficients between precipitation indices and GMST were investigated, and the statistical significance was assessed at the 5% level. With the exceptions of SDII and Rx1day, all other precipitation indices (PRCPTOT, PRCLTOT, PRCMTOT, PRCHTOT, RR, PRCLF, PRCMF and PRCHF) have statistically negative correlations with GMST. The sensitivity value is attained by calculating the ratio of linear trends of precipitation indices and GMST during 1987–2017. The regional median sensitivity, percentage change in the PRCPTOT, RR, SDII and Rx1day per 1- kelvin increase in GMST is –6.1%, –11.2%, 12.9% and 2.8%, respectively. Previous studies have indicated that the increase in global mean precipitation is merely 1–3% K-1 over the world (Feng et al. 2019). In contrast, our results show that the total annual precipitation will decrease by 6.1% K-1 over Iran.

While our results are generally consistent with the results of previous studies that have examined the precipitation change in Iran (Javari et al. 2016; Khalili et al. 2016; Daneshvar et al. 2019; Alavinia and Zarei 2020; Sharafi and Mir Karim 2020; Doostan 2020; Sadeghinia et al. 2022a), our findings provide a more detailed analysis of precipitation behavior in Iran, because we have examined changes in the characteristics (amount, frequency and intensity) of precipitation events of different intensities (light, moderate, heavy precipitation). The results in this paper indicate that dividing daily precipitation events into several categories is useful for a more detailed analysis of precipitation events.

The results of the present study are notably consistent with previous studies conducted over the subtropical regions (Trenberth et al. 2007; Trenberth 2011; Caloiero et al. 2018; Mathbout et al. 2018; Nicholson et al. 2018). Many studies have reported on the decreasing trends in total annual precipitation and the number of wet days in subtropical regions such as Iran. Most models agree that precipitation will increase in equatorial and high-latitude regions and decrease in subtropical regions. Based on these changes, the "wet places become wetter and dry places become drier" (Held and Soden 2006; Trenberth et al. 2011). Downward trends in subtropical precipitation are a robust response to global warming. Many reasons have been given for the decline in precipitation in these regions. Intensification of dryness in subtropical regions can be related to the thermodynamic increase in vapor transport (Held & Soden 2006) and a poleward shift of subtropical subsidence associated with the poleward expansion of the Hadley cell (Scheff and Frierson 2012). According to recent studies, precipitation change in subtropical regions should be interpreted as a response to the land–sea warming contrast, the direct radiative forcing of CO_2, and the patterns of sea surface temperature (SST) change (He and Soden 2017). Also, a strong anomalous ridge drives a regional precipitation decline in the Mediterranean Basin (Tuel and Eltahir 2020). Future studies are necessary to understand the relationship between changes in atmospheric circulation fully and their contribution to the observed changes in the amount, frequency and intensity of precipitation over Iran.

The intense decrease in the amount and frequency of precipitation in arid and semi-arid Iran in the twenty-first century will severely affect water resources if no additional adaptation measures are taken. Therefore, it is important to encourage more studies on the impacts of climate change on human health, terrestrial ecosystems, water resources, and agriculture and energy systems.

There were limitations in this study. One of these limitations is related to the lack of stations in some regions of Iran. The vast majority of stations are located in western Iran, and the central and eastern regions are much less well sampled. There is an urgent need to improve data collection in regions where the station records are limited in order to better identify changes in precipitation and other climate variables.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author contributions

Study design: AS; data collection AS, SR, HN; statistical analysis: AS, HN; result interpretation: HN, SR; manuscript preparation: AS, SR, NH; literature review: AS, SR, NH.

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