Assessment of changes in climate extremes of temperature and precipitation over Iran

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Abstract

Intense industrial activity has led to an increase in greenhouse gas concentration in the Earth's atmosphere over the past few decades, whereby the climate change phenomenon has been recognized. Increasing greenhouse gases have been changing patterns and trends of extreme climate variables that are of great importance in agriculture, water resources, and environmental hazards. In the present study, the changes and trends in climate extremes of temperature and precipitation were evaluated based on various extreme-related indices over Iran. For this purpose, both daily temperature and precipitation data of 76 synoptic stations were selected for trend analysis throughout Iran during the period 1981–2010. The nonparametric Mann-Kendall trend test and Sen's slope estimator are used to investigate the trends in the selected data sets. The results of 11 extreme temperature-related indices showed, in general, warm indices such as the number of warm days (TX90p), warm nights (TN90p), and warm spell duration (WSDI) had an increasing trend whereas trends in cold indices such as the number of cool days (TX10p), cool nights (TN10p), and cold spell duration (CSDI) decreased. The monthly maximum value of daily maximum (TXx) and minimum (TNx) temperatures increased by 0.3 and 0.4 °C/decade on average, respectively; and the monthly minimum value of daily maximum (TXn) and minimum (TNn) temperatures increased by 0.1 and 0.3 °C/decade, respectively, on average during the study period. In the case of the extreme precipitation-related indices, the results indicated both a decreasing trend in precipitation amount and intensity, and an increasing trend in the number of consecutive dry days (CDD) at most of the selected stations. Surveys demonstrated that the western, northern, and northwestern regions of Iran were most affected by the risk of climate extremes. Thus, these extreme changes will make people more vulnerable to natural hazards and make proper management in the face of climate crises more necessary.

1 Introduction

Nowadays, the topics of climate change and global warming have attracted the attention of all researchers regarding the future climate status of the world (IPCC 2001). During the past decades, most of the studies conducted on global climate change have focused mainly on changes in mean observations of temperature and precipitation data; however, there are a few types of research on climate extremes (Shrestha et al. 2017; Mohan et al. 2020). Hence, since climate change has become more important in recent decades, the studies assessing the past climate trends in climate extremes of temperature and precipitation have significantly progressed (Kharin and Zwiers 2000; Alexander et al. 2006; Whan et al. 2014; Ávila et al. 2016; Karki et al. 2017; Shrestha et al. 2017; Nkemelang et al. 2018). Furthermore, a few studies exist regarding the assessment of trends in climate extremes for a better and more precise understanding of changes that have already occurred in global climate conditions around the world (Nicholls et al. 1996).

Concerning the assessment of trends and changes in climate extremes, several studies have been conducted on basin and country scale over different parts of the world. Iran is located in the arid and semi-arid belt of the northern

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hemisphere as well as exposed to climate change hazards, but no comprehensive study has yet been done to identify the trends and changes in its climate extremes. Recently, Rahimzadeh et al. (2009), Balling et al. (2016), and Soltani et al. (2016) studied the variability of extreme temperature and precipitation in Iran with fewer stations and climate indices. However, some studies have been carried out in Iran to identify the trends and changes in various hydroclimatic variables on mean observational data, not on climate extremes (Modarres and Sarhadi 2009; Dinpashoh et al. 2011; Razei et al. 2014; Modarres et al. 2016; Mianabadi et al. 2019). In the following, some related studies conducted around the world are briefly mentioned.

Changes and trends in Asia's weather extremes were assessed by Klein Tank et al. (2006) during the period 1961–2000. The results revealed the number of warm days/ nights increased and the number of cool days/nights decreased at most of the stations. A study by You et al. (2008) revealed the changes in temperature extremes for the Tibetan Plateau region from 1961 to 2005. They found a decreasing trend in cool days/nights together with an increasing trend in warm days/nights in most of the stations revealing statistically significant trends. Cropper and Cropper (2016) investigated the trends of climate variability in Sheffield, England, using indices of the RClimdex model; moreover, the results showed the annual and seasonal increasing trends in precipitation extremes in the future period. Ávila et al. (2016) identified the changes in precipitation extremes using the RClimdex model in southern Brazil for the period 1978–2014. They found the changes have increasing trend in all seasons except winter. Shrestha et al. (2017) studied the changes and trends in daily climate extremes such as temperature and precipitation over the Koshi River basin, shared among China, Nepal, and India, for the period 1975–2010. The results showed an increase in both frequency and intensity of weather extremes such as the number of warm days and nights and maximum and minimum temperatures. In another study, Wang et al. (2016), by examining the trend of changes in precipitation extremes, found that the precipitations have decreased overall from west to east.
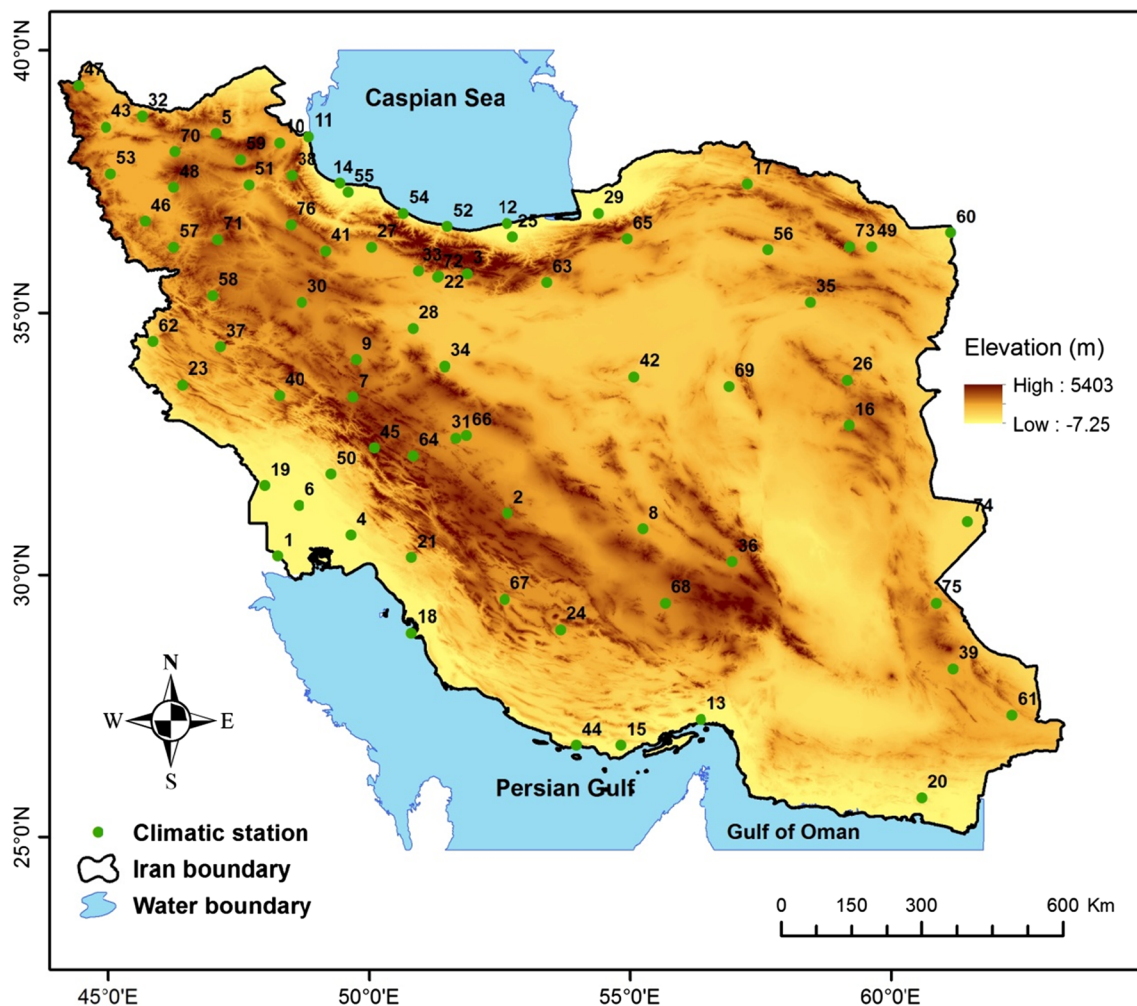

Fig. 1 Geographical location of the selected stations in this study

Table 1 List of the selected synoptic stations used in this study

S. No.	Station name	Lon. (E)	Lat. (N)	Alt. (m)	S. No.	Station name	Lon. (E)	Lat. (N)	Alt. (m)
1	Abadan	48.25	30.36	6.6	39	Khash	61.2	28.216	1394.0
2	Abadeh	52.66	31.18	2030.0	40	Khorram Abad	48.28	33.43	1147.8
3	Abali	51.88	35.75	2465.2	41	Khoramdare	49.18	36.18	1575.0
4	Aghajari	49.66	30.76	27	42	Khor-Biabanak	55.08	33.78	845.0
5	Ahar	47.07	38.43	1390.5	43	Khoy	44.96	38.55	1103.0
6	Ahvaz	48.66	31.33	22.5	44	Kish	53.98	26.75	30.0
7	Aligodarz	49.70	33.40	2022.0	45	Koohrang	50.11	32.43	2285.0
8	Anar	55.25	30.88	1408.8	46	Mahabad	45.716	36.75	1351.8
9	Arak	49.76	34.10	1708.0	47	Makoo	44.43	39.33	1411.3
10	Ardabil	48.28	38.25	1332.0	48	Maragheh	46.26	37.4	1477.7
11	Astara	48.85	38.37	− 21.1	49	Mashhad	59.63	36.26	999.2
12	Babolsar	52.65	36.71	− 21.0	50	Masjed Soleiman	49.28	31.93	320.5
13	Bandar Abbas	56.36	27.25	9.8	51	Mianeh	47.7	37.45	1110.0
14	Bandar Anzali	49.45	37.48	− 23.6	52	Noshahr	51.5	36.65	− 20.9
15	Bandar Lengeh	54.83	26.75	22.7	53	Oromiyeh	45.05	37.66	1328.0
16	Birjand	59.20	32.86	1491.0	54	Ramsar	50.66	36.9	− 20.0
17	Bojnord	57.26	37.46	1112.0	55	Rasht	49.61	37.31	− 8.6
18	Boshehr	50.82	28.90	9.0	56	Sabzevar	57.65	36.2	972.0
19	Bostan	48.00	31.71	7.8	57	Saghez	46.26	36.25	1522.8
20	Chabahar	60.61	25.75	8.0	58	Sanandaj	47	35.33	1373.4
21	Dogonbadan	50.82	30.33	726.0	59	Sarab	47.53	37.93	1682.0
22	Doshan Tapeh	51.33	35.70	1209.2	60	Sarakhs	61.16	36.53	235.0
23	Ilam	46.43	33.63	1337.0	61	Saravan	62.33	27.33	1195.0
24	Fasa	53.68	28.96	1288.3	62	Sarpol-e Zahab	45.86	34.45	545.0
25	Ghaemshahr	52.76	36.45	14.7	63	Semnan	53.41	35.58	1127.0
26	Ghaen	59.17	33.72	1432.0	64	Shahrekord	50.85	32.28	2048.9
27	Ghazvin	50.05	36.25	1279.2	65	Shahrood	54.95	36.41	1349.1
28	Ghom	50.85	34.70	877.4	66	Sharghe Isfahan	51.86	32.67	1543.0
29	Gorgan	54.40	36.90	00.0	67	Shiraz	52.6	29.53	1484.0
30	Hamedan	48.71	35.20	1679.7	68	Sirjan	55.68	29.46	1739.4
31	Isfahan	51.66	32.62	1550.4	69	Tabas	56.91	33.6	711.0
32	Jolfa	45.66	38.75	736.2	70	Tabriz	46.28	38.083	1361.0
33	Karaj	50.95	35.80	1300.0	71	Takab	47.1	36.4	1817.2
34	Kashan	51.45	33.98	982.3	72	Tehran	51.31	35.68	1190.8
35	Kashmar	58.46	35.20	1109.7	73	Torbat Heydariyeh	59.21	36.26	1450.8
36	Kerman	56.97	30.25	1753.8	74	Zabol	61.48	31.02	489.2
37	Kermanshah	47.15	34.35	1318.6	75	Zahedan	60.88	29.46	1370.0
38	Khalkhal	48.52	37.63	1796.0	76	Zanjan	48.5	36.68	1663.0

Since temperature and precipitation are two essential variables in determining the climate of a region, their changes affect different hydroclimate systems directly and indirectly. Additionally, changes in climate events in terms of their frequency and intensity have a powerful impact on the environment and society of that region. In this context, the objective of the present study is to assess the changes and trends in the climate extremes of daily temperature and precipitation based on various extreme-related indices over Iran during the period 1981–2010. For identifying the monotonic linear trends, the nonparametric Mann-Kendall trend test and Sen's slope estimator, as well as their spatial analysis, are investigated in the selected Iranian data sets. The present study, one of the most comprehensive nationwide researches in Iran, can help researchers to achieve a better understanding of changes in climate indices over Iran.

Table 2 Climate indices suggested by ETCCDI used in this study

ID	Index name	Definition	Unit
TXx	Max. *T*max	Monthly maximum value of daily maximum temperature	°C
TXn	Min. *T*max	Monthly minimum value of daily maximum temperature	°C
TNx	Max. *T*min	Monthly maximum value of daily minimum temperature	°C
TNn	Min. *T*min	Monthly minimum value of daily minimum temperature	°C
TX10p	Cool days	Percentage of days when TX < 10th percentile	% days
TX90p	Warm days	Percentage of days when TX > 90th percentile	% days
TN10p	Cool nights	Percentage of days when TN < 10th percentile	% days
TN90p	Warm nights	Percentage of days when TN > 90th percentile	% days
WSDI	Warm spell duration index	Annual count of days with at least 6 consecutive days when TX > 90th percentile	%
CDSI	Cold spell duration index	Annual count of days with at least 6 consecutive days when TN < 10th percentile	%
DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C
RX1day	Max. 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
RX5day	Max. 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as PRCP $\geq$ 1.0 mm) in the year	mm
R10	Number of heavy precipitation days	Annual count of days when PRCP $\geq$ 10 mm	days
R20	Number of very heavy precipitation days	Annual count of days when PRCP $\geq$ 20 mm	days
CDD	Consecutive dry days	Maximum number of consecutive days with RR < 1 mm	days
CWD	Consecutive wet days	Maximum number of consecutive days with RR $\geq$ 1 mm	days
R95p	Very wet days	Annual total PRCP when RR > 95th percentile	mm
R99p	Extremely wet days	Annual total PRCP when RR > 99th percentile	mm
PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR $\geq$ 1 mm)	mm

TX, daily maximum temperature; *TN*, daily minimum temperature; *PRCP*, precipitation

2 Method

2.1 Study area and data

Iran as a relatively large country (1,648,195 km^2), located in an arid and semi-arid region of the world (roughly between longitudes 25°–40° N and latitudes 45°–65° E). Although most of Iran's territory is plateau, two great mountain belts are situated in the northern (Elburz Mountains) and western (Zagros Mountains) regions. Given that these two mountainous regions prevent moisture from reaching Iran's central plateau, both large and local atmospheric systems affect Iran's climate. The temporal and spatial variability in hydrometeorological variables (such as precipitation and temperature) are affected by these two atmospheric systems (Modarres et al. 2016). On the southern coast of the Caspian Sea, the annual amount of precipitation reaches about 2000 mm, while in the central and eastern parts of the country; it is less than 50 mm. The highest amount of precipitation occurs largely in the winter and autumn seasons. Iran, due to receiving low atmospheric precipitation, one-third of the global mean (i.e., about 250 mm), has an inappropriate distribution of precipitation. In addition, floods mainly occurring in the north and west, as well as droughts, have extensively influenced the country over the last few decades.

The data used in the present study include daily precipitation and temperature data of 76 synoptic stations in Iran. These long-term climatological data were acquired from Iran Meteorological Organization (www.irimo.ir) for the period 1981–2010. The geographical locations of the selected stations are depicted in Fig. 1 and other descriptive information is presented in Table 1. Because of the prevalence of precipitation in the north and west, most stations were selected in those regions. The eastern half of the country from the northeast to the southeast and the center include fewer stations because these regions have little rainfall, and the vast expanse is deserts, namely Dasht-e Kavir and Dasht-e Lut. Note that the numbers next to the position of stations (green-colored circles) in Fig. 1 denote the station number appearing in Table 1.

2.2 Climate indices and trend analysis

The extreme climate indices are calculated from daily temperature and precipitation data using the RClimDex software (http://cccma.seos.uvic.ca/ETCCDI/RClimDex/rclimdex.r). The software is user friendly, calculates the climate extreme–related indices, and runs under the R programming environment (http://www.r-project.org/). The RClimDex software has been used in many studies (e.g., Islam 2009; Donat et al. 2013;

Table 3 Slope of trends in temperature-related indices during the study period

Station name	TXx	TXn	TNx	TNn	TX10p	TX90p	TN10p	TN90p	WSDI	CSDI	DTR
Abadan	0.032	− 0.073	0.069	0.028	− 0.348	0.388	− 0.600	0.485	0.361	− 0.356	− 0.022
Abadeh	0.007	− 0.143	0.013	− 0.090	0.062	− 0.175	0.030	− 0.126	− 0.131	− 0.104	− 0.001
Abali	0.079	0.054	0.038	0.068	− 0.324	0.660	− 0.253	0.305	0.992	− 0.227	0.040
Aghajari	0.027	− 0.051	0.072	0.045	− 0.217	0.316	− 0.611	0.467	0.313	− 0.240	− 0.039
Ahar	0.066	− 0.027	0.014	− 0.041	− 0.258	0.467	− 0.194	0.254	0.497	0.022	0.035
Ahvaz	0.001	− 0.048	0.084	0.045	− 0.213	0.257	− 0.715	0.605	0.325	− 0.410	− 0.048
Aligodarz	0.029	0.019	0.016	0.026	− 0.278	0.272	− 0.291	0.163	0.407	− 0.201	0.025
Anar	0.063	0.005	0.130	− 0.044	− 0.298	0.416	− 0.090	0.141	0.565	− 0.127	0.029
Arak	0.045	0.008	0.080	0.058	− 0.229	0.319	− 0.443	0.341	0.490	− 0.281	− 0.007
Ardabil	0.036	0.046	0.054	0.098	− 0.253	0.299	− 0.188	0.328	0.188	− 0.092	0.011
Astara	0.073	0.028	0.052	0.002	− 0.296	0.472	− 0.212	0.561	0.676	0.010	0.019
Babolsar	0.022	0.020	0.047	0.070	− 0.173	0.232	− 0.530	0.608	0.417	− 0.319	− 0.044
Bandar Abbas	0.019	− 0.057	0.033	− 0.047	− 0.238	0.217	− 0.321	0.409	0.364	− 0.229	− 0.010
Bandar Anzali	− 0.044	0.040	0.066	0.060	− 0.118	− 0.087	− 0.414	0.532	− 0.092	− 0.314	− 0.050
Bandar Lengeh	0.045	− 0.041	0.027	− 0.030	− 0.243	0.501	− 0.380	0.424	1.261	0.451	− 0.002
Birjand	0.047	0.002	0.041	− 0.106	− 0.215	0.388	− 0.326	0.387	0.394	− 0.219	− 0.015
Bojnord	− 0.020	0.033	0.009	0.053	− 0.088	0.059	− 0.123	0.110	0.069	0.040	− 0.008
Boshehr	− 0.106	− 0.029	0.028	0.040	− 0.176	− 0.007	− 0.320	0.448	0.055	− 0.134	− 0.047
Bostan	0.039	− 0.091	0.117	0.024	− 0.557	0.549	− 0.753	0.697	0.150	− 0.387	− 0.013
Chabahar	0.106	− 0.007	0.057	− 0.033	− 0.703	0.502	− 0.629	0.826	0.495	− 0.184	− 0.008
Dogonbadan	− 0.034	0.005	0.057	0.103	0.223	− 0.019	− 0.580	1.136	− 0.010	− 0.541	− 0.129
Doshan Tapeh	0.050	0.039	0.062	0.108	− 0.190	0.247	− 0.506	0.484	0.594	− 0.369	− 0.049
Ilam	0.065	0.063	− 0.123	0.014	− 0.515	0.833	0.610	− 0.202	1.710	0.265	0.170
Fasa	0.027	− 0.004	− 0.011	− 0.073	− 0.086	0.014	0.002	− 0.367	0.516	− 0.068	0.043
Ghaemshahr	0.121	0.019	0.046	0.008	− 0.282	0.362	− 0.245	0.272	0.216	− 0.096	0.024
Ghaen	0.176	0.117	0.158	0.083	− 0.291	1.111	− 0.499	1.167	3.389	0.034	− 0.025
Ghazvin	0.028	0.087	0.018	0.093	− 0.353	0.403	− 0.401	0.236	0.643	− 0.226	0.018
Ghom	0.049	0.034	0.088	0.010	− 0.260	0.291	− 0.490	0.558	0.398	− 0.093	− 0.034
Gorgan	− 0.009	0.025	0.035	− 0.044	− 0.229	0.267	0.026	0.148	0.169	0.030	0.042
Hamedan	0.023	0.050	0.081	0.088	− 0.156	0.163	− 0.588	0.305	0.410	− 0.333	− 0.055
Isfahan	0.069	− 0.021	0.012	− 0.039	− 0.306	0.449	0.101	0.047	0.661	0.056	0.069
Jolfa	− 0.020	− 0.087	− 0.004	− 0.120	− 0.021	0.152	− 0.073	0.326	0.294	0.025	− 0.018
Karaj	0.073	0.029	0.081	0.071	− 0.340	0.508	− 0.439	0.411	0.830	− 0.243	− 0.007
Kashan	0.011	0.005	0.001	− 0.025	− 0.083	− 0.151	− 0.184	0.196	− 0.340	− 0.017	− 0.039
Kashmar	0.042	0.014	0.056	− 0.048	− 0.197	0.377	− 0.080	0.335	0.575	0.297	0.020
Kerman	0.055	0.006	0.093	0.035	− 0.280	0.362	− 0.350	0.330	0.545	− 0.421	− 0.011
Kermanshah	0.054	0.121	0.038	0.057	− 0.464	0.588	− 0.377	0.342	0.725	− 0.124	0.043
Khalkhal	0.008	0.028	0.047	0.217	− 0.333	0.478	− 0.578	0.457	0.823	− 0.139	− 0.039
Khash	0.027	0.021	0.081	− 0.028	− 0.346	0.451	− 0.309	0.208	0.507	− 0.192	0.012
Khorram Abad	0.031	0.016	0.093	0.085	− 0.319	0.464	− 0.603	0.392	0.755	− 0.254	− 0.031
Khoramdare	0.018	0.047	0.069	0.089	− 0.343	0.295	− 0.594	0.652	0.497	− 0.464	− 0.037
Khor-Biabanak	0.046	− 0.029	0.015	0.022	− 0.196	0.362	− 0.432	0.547	0.298	− 0.070	− 0.026
Khoy	0.042	− 0.026	0.023	− 0.092	− 0.210	0.464	− 0.349	0.402	0.756	− 0.071	0.006
Kish	0.015	− 0.003	0.039	0.131	− 0.339	0.185	− 0.770	0.716	0.201	− 0.268	− 0.065
Koohrang	− 0.009	0.099	− 0.032	0.097	− 0.329	0.400	− 0.206	0.196	1.023	− 0.115	0.026
Mahabad	− 0.004	0.043	0.045	− 0.042	− 0.376	0.310	− 0.453	0.347	0.222	− 0.213	0.005
Makoo	0.057	0.042	0.041	0.006	− 0.269	0.482	− 0.345	0.397	0.906	− 0.314	0.001
Maragheh	0.063	0.103	− 0.009	− 0.007	− 0.602	0.837	− 0.528	0.608	1.258	− 0.374	0.054
Mashhad	0.066	− 0.025	0.031	0.204	− 0.134	0.299	− 0.703	0.566	0.175	− 0.807	− 0.068

Table 3 (continued)

Station name	TXx	TXn	TNx	TNn	TX10p	TX90p	TN10p	TN90p	WSDI	CSDI	DTR
Masjed Soleiman	0.045	− 0.020	0.030	0.056	− 0.300	0.418	− 0.260	0.104	0.614	− 0.298	0.041
Mianeh	0.025	0.119	0.022	0.195	− 0.471	0.495	− 0.624	0.689	0.814	− 0.435	0.004
Noshahr	0.057	0.072	0.040	0.022	− 0.234	0.366	− 0.317	0.430	0.666	− 0.203	− 0.004
Oromiyeh	0.036	0.049	0.019	0.023	− 0.422	0.536	− 0.299	0.230	0.706	− 0.501	0.043
Ramsar	0.089	0.042	0.065	0.081	− 0.185	0.435	− 0.582	0.664	0.829	− 0.441	− 0.039
Rasht	0.027	− 0.015	0.048	0.019	− 0.089	0.199	− 0.272	0.333	0.259	− 0.158	− 0.002
Sabzevar	0.036	0.034	− 0.016	− 0.003	− 0.133	0.189	0.033	0.176	0.278	0.116	0.024
Saghez	− 0.038	0.089	− 0.032	0.047	− 0.245	0.150	− 0.008	− 0.154	0.366	− 0.079	0.074
Sanandaj	0.016	0.022	0.058	0.280	− 0.360	0.541	− 0.754	0.355	1.123	− 0.610	− 0.029
Sarab	0.049	0.086	0.017	0.144	− 0.374	0.473	− 0.179	0.312	0.777	− 0.018	0.031
Sarakhs	0.019	− 0.067	0.011	0.011	− 0.131	0.258	− 0.314	0.295	0.120	− 0.117	− 0.007
Saravan	0.014	− 0.130	0.119	0.060	− 0.249	0.574	− 0.434	0.361	1.045	− 0.123	0.001
Sarpol-e Zahab	0.108	0.049	0.178	0.037	− 0.436	0.533	− 0.614	0.365	0.706	− 0.361	0.002
Semnan	0.024	0.030	− 0.019	− 0.030	− 0.002	0.192	0.226	0.114	0.268	1.198	0.026
Shahrekord	0.016	− 0.114	− 0.088	− 0.238	− 0.140	− 0.155	0.399	− 0.141	− 0.071	0.234	0.061
Shahrood	0.033	0.053	0.066	0.096	− 0.216	0.137	− 0.484	0.414	0.224	− 0.584	− 0.042
Sharghe Isfahan	0.108	− 0.011	0.123	0.097	− 0.177	0.295	− 0.719	0.560	0.890	− 0.721	− 0.064
Shiraz	0.014	− 0.044	0.057	− 0.028	− 0.245	0.134	− 0.348	0.307	0.219	− 0.198	− 0.015
Sirjan	0.015	− 0.003	0.088	0.033	− 0.149	0.098	− 0.253	0.407	0.248	− 0.272	− 0.026
Tabas	0.005	0.037	0.012	0.018	− 0.158	0.290	− 0.290	0.602	0.344	0.048	− 0.027
Tabriz	0.021	0.077	0.012	0.071	− 0.404	0.544	− **0**.303	0.316	0.792	− 0.221	0.037
Takab	0.027	0.100	− 0.018	0.140	− 0.388	0.410	− 0.356	0.311	0.949	− 0.071	0.019
Tehran	0.053	0.055	0.031	0.074	− 0.297	0.409	− 0.394	0.388	0.695	− 0.194	− 0.008
Torbat Heydariyeh	− 0.015	− 0.029	− 0.002	− 0.036	0.046	− 0.203	− 0.065	0.209	− 0.279	− 0.051	− 0.042
Zabol	0.066	0.003	0.088	− 0.100	− 0.210	0.578	− 0.075	0.475	0.442	− 0.084	0.034
Zahedan	0.014	0.046	0.081	− 0.024	− 0.121	0.309	− 0.177	0.185	0.161	− 0.111	0.001
Zanjan	0.004	0.062	− 0.005	0.086	− 0.262	0.270	− 0.219	0.074	0.678	− 0.158	0.029
Average	0.03	0.01	0.04	0.03	− 0.25	0.34	− 0.33	0.36	0.53	− 0.17	0.00
Stations having positive trend	64	48	63	51	3	69	7	71	70	14	30
Stations having negative trend	9	23	10	23	72	7	68	5	6	62	37
Stations having no trend	3	5	3	2	1	0	1	0	0	0	9

Italic numbers denote statistically significant trends at 5% critical level

Whan et al. 2014; Ávila et al. 2016; Wang et al. 2016; Shrestha et al. 2017; Mohan et al. 2020) as the standard tool for obtaining climate indices. This software facilitates the calculation of 27 indices, including 11 precipitation-related indices and 16 temperature-related indices (Wang and Feng 2010) developed by the Expert Team on Climate Change Detection and Indices (ETCCDI), the World Climate Research Programme (WCRP), and the Commission for Climatology (CC). The 21 indices are selected to assess the climate extremes in Iran listed in Table 2. In the case of the trend analysis in the climate extremes indices, the nonparametric Mann-Kendall (MK) trend test (Mann 1945; Kendall 1975) and Sen's slope estimator (Sen 1968) were applied. The MK is a well-known nonparametric test and its best point is that the test does not require the data be normally distributed (Nourani et al. 2015). The MK test is one of the most widely used methods for identification of trends in climatic variables. Thus, the MK was used to detect whether monotonic increasing or decreasing trends exist in the data sets, while Sen's slope estimator presents the trend slope for each data set. If the p value is less than 0.05, a significant trend exists in the data set at the 95% confidence level. Readers can refer to Fathian et al. (2015) and Mohan et al. (2020) for more details about the formulas and how to use these methods.

3 Results and discussion

3.1 Temperature-related indices

Table 3 shows the results of the trend analysis and the estimated slopes of the trend line for the temperature-related
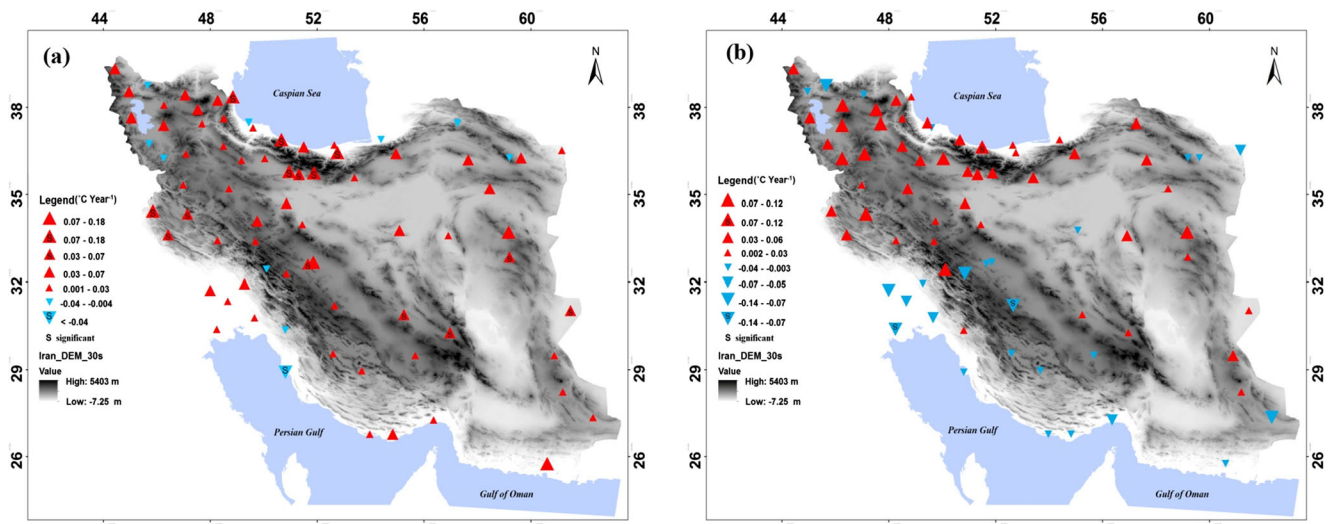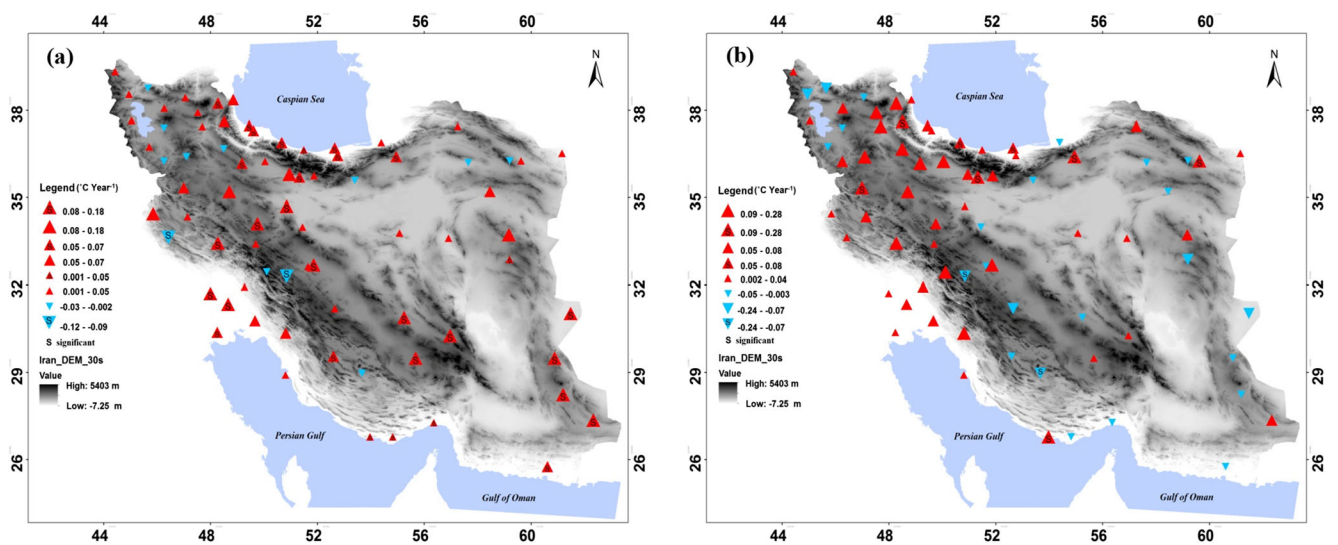
Fig. 2 Trends in monthly **a** maximum and **b** minimum values of daily maximum temperatures (TXx, TXn) (the red up-pointing and turquoise down-pointing triangles designate the increasing and decreasing trends, respectively)

indices obtained from maximum and minimum daily temperatures for all 76 selected stations. Note that the table's italic numbers designate statistically significant trends detected by the Mann-Kendall trend test at the 5% critical level. The TXx index exhibited an increasing trend at 64 out of 76 stations (15 statistically significant), and nine stations showed a decreasing trend (1 statistically significant). The TXx generally increased on average by 0.3 °C/decade, and most of the stations with a statistically significant increase are located in the north (Fig. 2a). Regarding the TXn index, an increasing trend was observed at a majority of the stations (48 out of 76, 1 statistically significant), and 23 stations had a decreasing trend (2 statistically significant). Figure 2 b designates that these stations with positive trends are mostly situated in the north and northwest. The trend of the TNx index increased at 63 stations

(30 statistically significant), and the slope of the trend line was at a rate of 0.4 °C/decade on average. Figure 3 a shows that, except the northeast and northwest, the TNx trend has significantly increased. Most stations with significant increase trends are located in the southeast and southwest as well as on the central coast of both the Caspian Sea and the Persian Gulf (Fig. 3a). The TNn index showed an increase of 0.3 °C/decade on average, so 51 out of 76 stations showed a positive trend (8 statistically significant), and 24 stations showed a negative trend (2 statistically significant). Most stations with the highest increase trend are located in the north and northwest (Fig. 3b).

The results of our study are in accordance with Koozegaran and Mousavai Bayegi (2015). They presented both TXx and TNx with an insignificant increasing trend in all northeastern

Fig. 3 Trends in monthly **a** maximum and **b** minimum values of daily minimum temperatures (TNx, TNn) (the red up-pointing and turquoise down-pointing triangles designate the increasing and decreasing trends, respectively)
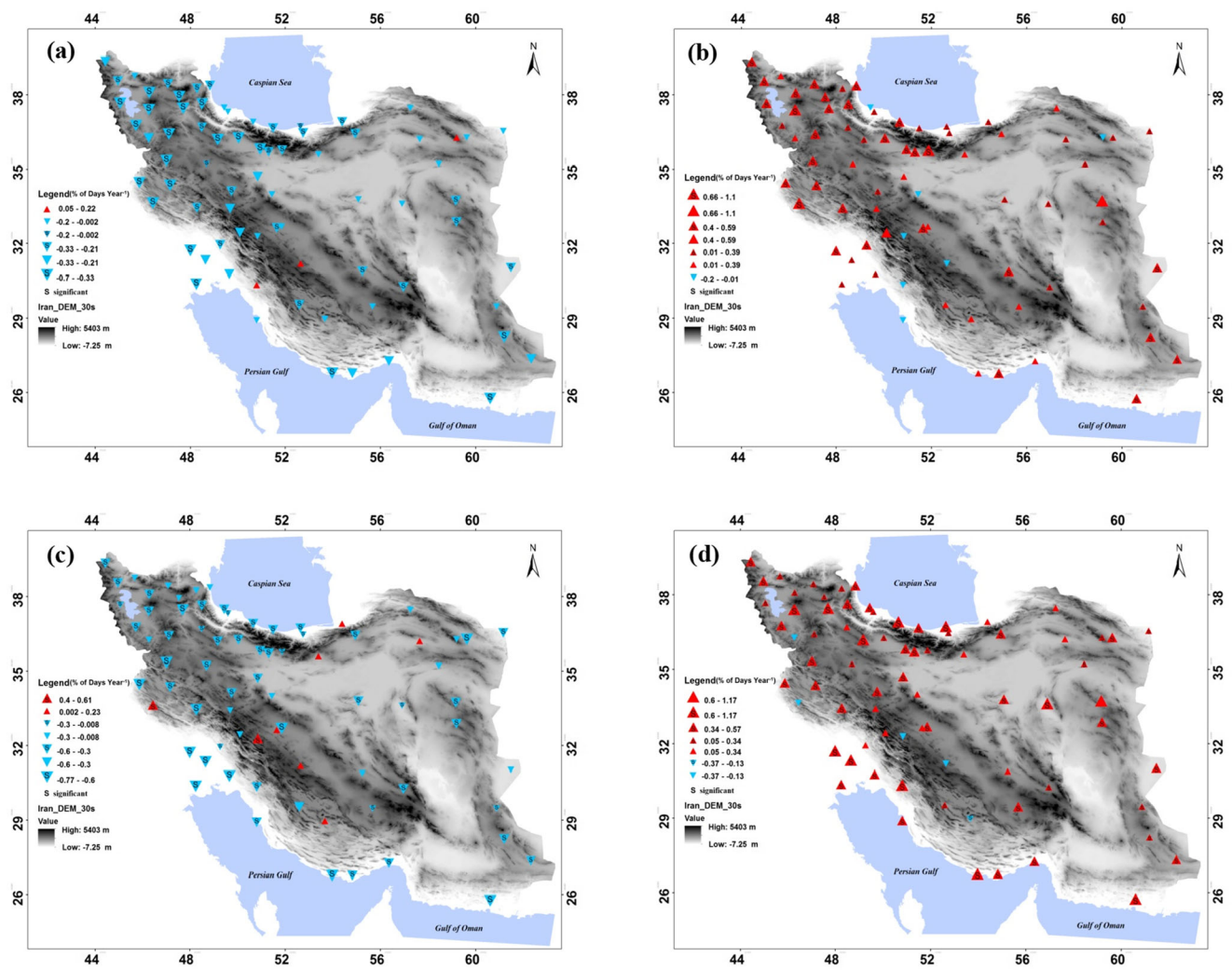
Fig. 4 Trends in the number of **a** cool days (TX10p), **b** warm days (TX90p), **c** cool nights (TN10p), and **d** warm nights (TN90p) (the red up-pointing and turquoise down-pointing triangles designate the increasing and decreasing trends, respectively)
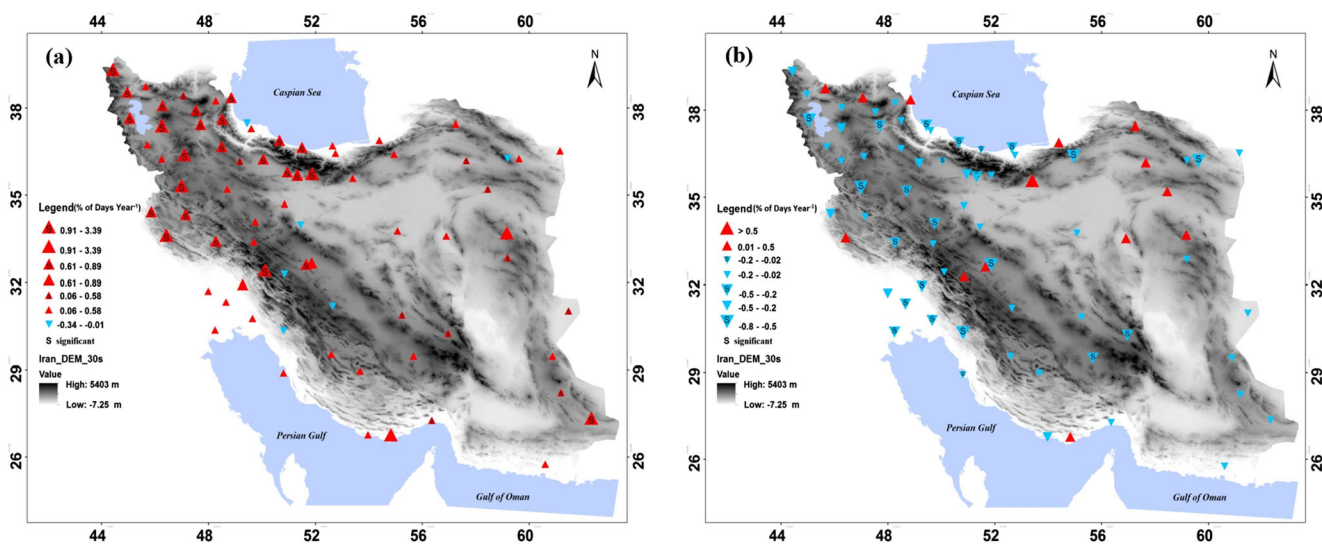
Fig. 5 Trends in **a** warm spell duration index (WSDI) and **b** cold spell duration index (CSDI) (the red up-pointing and turquoise down-pointing triangles designate the increasing and decreasing trends, respectively)

Fig. 6 Trends in the diurnal temperature range (DTR) (the red up-pointing and turquoise down-pointing triangles designate the increasing and decreasing trends, respectively)
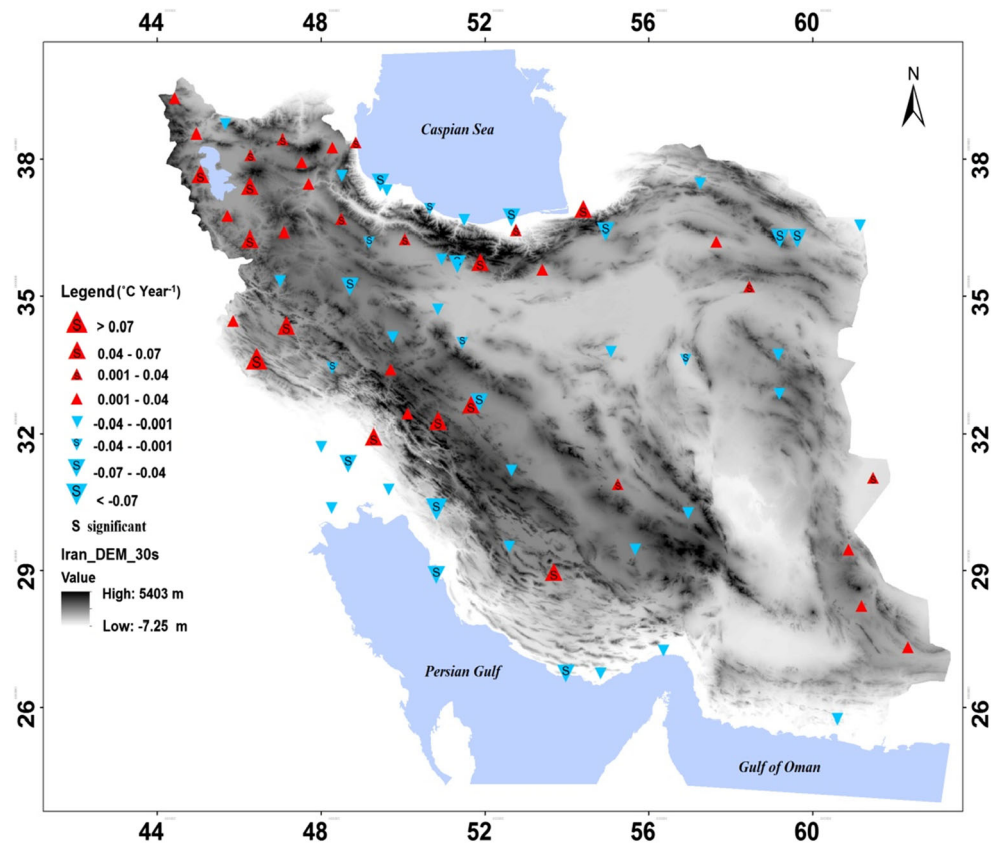
stations. In addition, according to the findings of Alijani and Farajzadeh (2015), the trend of changes exhibited an increase in the TXn in almost all parts of northwestern Iran, while the results showed a decrease in the TNn at most stations. These findings agree with the results of our study in this region. The assessment of changes in temperature-related indices in some Iranian stations by Rahimzadeh et al. (2009) demonstrated that the TXn, TNx, and TNn had an increasing trend in most stations and the present study agrees with their results.

The trend in the number of cool days (TX10p) decreased for 72 stations (44 statistically significant) at an overall rate of −2.5% per decade. Figure 4 a presents the lowest values of this significant decrease trend, observed in the north, west, and northwest. The trend in the number of warm days (TX90p) increased at 69 stations (53 statistically significant) by 3.4% per decade on average, and most were seen in the north, northwest, and west (Fig. 4b). Warming trends were observed through a decrease in the frequency of cool nights (TN10p) by −3.3% per decade on average, and an increase in the number of warm nights (TN90p) by 3.6% per decade on average. Sixty-eight stations (55 statistically significant) showed the decreasing trend in TN10p almost throughout Iran, and stations having the highest negative trends are situated in the west and northwest (Fig. 4c). The increasing trend was observable in TN90p at 71 stations (59 statistically significant)

and this widespread significant trend was seen throughout Iran (Fig. 4d).

Erfanian et al. (2014) carried out on a study in northeastern Iran in which the trends in TX10p and TN10p generally decreased. In contrast, their trends in TX90p and TN90p increased. The Rahimzadeh et al. (2009) assessment also showed an increase in TN90p and TX90p changes as well as a decrease in the TN10p and TX10p changes in many parts of the country. The present study agrees with their findings. According to Kiktev et al. (2003), this increase in the TN90p and TX90p indices is most likely due to global warming. Trenberth et al. (2007) found that the highest values of these indices have occurred in recent years. In research carried out by Soltani et al. (2016), the same results were obtained regarding theses indices; the annual frequency of warm days and nights was shown to have increased over the period 1995–2010 while the number of cool days and nights has decreased across Iran during the same period.

Concerning the warm spell duration index (WSDI), the results demonstrated a positive trend for 70 stations (36 statistically significant) by 5.3% per decade on average, in which the highest significant increasing trend is for stations mostly located in the north and northwest (Fig. 5a). The cold spell duration index (CSDI) showed a decrease of −1.7% per decade on average at 62 stations (23 statistically significant) located throughout Iran (Fig. 5b). The decreasing trend in

Table 4 Slope of trends in precipitation-related indices during the study period

Station name	RX1day	RX5day	SDII	R10	R20	CDD	CWD	R95p	R99p	PRCPTOT
Abadan	−0.21	−0.282	0.081	−0.036	−0.011	*1.833*	−0.015	0.200	−0.159	−1.103
Abadeh	0.149	0.223	0.037	0.013	0.000	−0.132	−0.003	0.198	0.294	−0.307
Abali	−0.046	−0.447	−0.048	−0.105	−0.062	0.297	0.039	−0.552	−0.067	−3.218
Aghajari	0.18	0.298	0.136	0.009	0.019	*2.566*	−0.037	2.385	−0.411	−0.277
Ahar	−0.197	−0.432	−0.040	*−0.189*	0.010	0.868	−0.032	−0.551	−0.294	*−4.571*
Ahvaz	−0.361	−0.497	−0.043	−0.109	−0.033	0.678	−0.024	−1.196	0.120	−3.382
Aligodarz	0.647	0.466	0.039	0.254	0.108	*−3.443*	0.021	2.665	1.520	7.028
Anar	−0.179	−0.695	−0.017	−0.060	0.000	4.112	−0.055	−0.846	−0.371	*−2.166*
Arak	−0.081	−0.264	−0.007	−0.082	−0.012	−0.221	−0.011	0.167	−0.147	−2.645
Ardabil	−0.223	−0.438	−0.014	−0.089	−0.043	0.412	−0.032	−1.341	−0.705	−2.655
Astara	−0.564	−0.967	0.005	−0.342	−0.045	0.653	−0.040	0.708	−2.356	−8.492
Babolsar	−0.778	−1.194	0.021	−0.150	−0.050	0.265	−0.058	−1.036	−1.938	−4.359
Bandar Abbas	−0.922	−0.942	−0.053	−0.062	−0.052	0.146	−0.016	*−2.380*	−0.483	−3.542
Bandar Anzali	−0.217	−0.567	−0.042	*−0.427*	*−0.300*	0.310	−0.015	−3.889	0.117	−14.233
Bandar Lengeh	−0.141	−0.318	−0.049	−0.067	−0.044	1.035	−0.005	−0.261	0.333	−2.126
Birjand	−0.083	−0.041	0.005	−0.040	0.006	1.090	−0.054	−0.062	0.433	−2.161
Bojnord	−0.089	−0.005	0.038	−0.008	0.015	0.549	−0.031	0.673	−0.337	−0.602
Boshehr	0.691	1.029	*0.141*	0.046	0.043	−0.149	0.013	1.418	0.890	1.063
Bostan	−0.023	−0.25	0.083	−0.173	0.029	−0.962	−0.028	−0.062	−0.669	−3.129
Chabahar	*1.375*	0.82	0.280	−0.094	0.010	1.753	−0.071	3.410	*1.618*	0.349
Dogonbadan	−0.638	−0.999	0.010	−0.185	−0.017	0.684	−0.021	−0.879	−1.043	−5.400
Doshan Tapeh	−0.185	−0.428	−0.010	−0.077	−0.007	−0.955	0.018	−0.261	−0.044	−1.880
Ilam	−0.403	−0.641	−0.081	*−0.362*	−0.220	−0.559	*−0.109*	−4.811	−0.931	*−12.957*
Fasa	−0.533	−1.026	−0.037	−0.098	−0.047	0.120	−0.017	−1.084	0.054	−3.540
Ghaemshahr	−0.025	−0.197	0.020	−0.077	−0.015	0.112	−0.059	0.255	0.489	−2.653
Ghaen	0.024	0.113	−0.019	−0.099	−0.035	2.286	−0.034	0.143	0.935	−3.694
Ghazvin	−0.01	−0.272	−0.001	*−0.149*	−0.032	1.361	−0.009	−1.094	0.166	*−3.709*
Ghom	0.442	0.529	0.022	0.078	0.016	0.477	−0.056	0.503	0.620	0.401
Gorgan	−0.057	−0.335	−0.001	*−0.204*	−0.050	0.932	−0.024	0.303	0.618	*−5.494*
Hamedan	0.137	0.06	0.001	−0.082	−0.005	−0.181	−0.025	−0.519	0.226	*−3.329*
Isfahan	0.158	−0.065	0.053	0.044	0.025	1.252	−0.001	1.055	0.240	0.847
Jolfa	−0.01	0.033	0.041	0.014	0.011	3.055	−0.051	0.784	0.240	0.584
Karaj	−0.168	−0.275	−0.023	0.002	−0.015	−0.826	0.005	−1.348	0.448	0.137
Kashan	−0.059	−0.055	−0.006	0.017	−0.033	−0.461	0.001	−0.970	−0.540	−0.611
Kashmar	*−0.671*	−0.932	*−0.099*	*−0.200*	−0.082	0.601	0.018	−2.128	−0.828	*−4.770*
Kerman	*−0.368*	−0.549	−0.011	−0.028	−0.024	1.419	−0.027	*−0.989*	*−0.626*	−1.819
Kermanshah	−0.243	−0.438	−0.015	*−0.231*	−0.054	−0.313	*−0.060*	−0.402	−0.226	*−6.113*
Khalkhal	−0.137	−0.39	0.016	−0.125	0.062	−0.118	−0.051	1.335	−0.493	−3.131
Khash	0.164	0.571	0.046	−0.008	−0.024	0.295	−0.012	0.585	0.463	−0.933
Khorram Abad	0.218	0.079	0.004	*−0.310*	−0.069	−0.140	−0.014	−0.122	1.239	*−5.788*
Khoramdare	−0.287	−0.464	−0.047	−0.095	−0.043	−0.272	−0.060	−1.651	0.029	−3.752
Khor-Biabanak	−0.36	−0.181	−0.081	−0.043	−0.031	2.383	−0.009	−1.052	0.020	−1.072
Khoy	−0.246	−0.369	−0.006	−0.127	−0.036	0.248	*−0.052*	−1.005	−0.560	*−3.764*
Kish	−1.13	−2.032	−0.093	−0.103	−0.029	0.890	0.004	−2.305	−1.201	−3.402
Koohrang	−1.2	*−4.551*	−0.180	−0.542	−0.350	−1.525	−0.074	−5.405	−0.625	−21.326
Mahabad	0.314	−0.304	0.021	−0.073	0.013	−0.850	−0.021	0.381	0.959	−1.683
Makoo	−0.159	−0.25	−0.003	−0.054	0.013	−0.643	−0.045	−0.311	−0.656	−0.767
Maragheh	−0.183	−0.397	−0.064	*−0.280*	−0.079	1.995	−0.017	−1.849	−0.014	*−7.767*
Mashhad	−0.32	−0.714	−0.028	*−0.176*	−0.032	−0.144	*−0.058*	−0.867	−0.614	*−3.930*

Table 4 (continued)

Station name	RX1day	RX5day	SDII	R10	R20	CDD	CWD	R95p	R99p	PRCPTOT
Masjed Soleiman	− 1.531	− 1.947	− 0.117	− 0.298	− 0.154	0.510	− 0.083	− 4.530	− 2.638	− 11.043
Mianeh	− 0.589	− 0.447	− 0.065	− 0.160	− 0.053	0.116	− 0.022	− 0.733	− 1.244	− 4.430
Noshahr	− 0.211	0.324	− 0.006	− 0.199	− 0.057	0.511	− 0.066	− 0.445	− 0.307	− 5.900
Oromiyeh	− 0.161	− 0.635	− 0.005	− 0.145	− 0.041	0.722	− 0.040	− 1.136	− 0.058	− 3.943
Ramsar	0.232	0.037	− 0.034	− 0.129	− 0.118	0.141	0.010	− 3.828	1.063	− 4.633
Rasht	− 0.881	− 1.834	− 0.052	− 0.355	− 0.236	0.236	− 0.043	− 4.454	− 0.745	− 12.680
Sabzevar	− 0.176	− 0.182	0.002	− 0.075	− 0.019	1.658	− 0.018	− 0.465	− 0.380	− 1.988
Saghez	− 0.469	− 1.329	− 0.060	− 0.413	− 0.163	0.156	− 0.097	− 2.837	− 1.262	− 9.816
Sanandaj	− 0.043	− 0.571	− 0.057	− 0.420	− 0.122	− 0.420	− 0.008	− 2.414	− 0.644	− 9.707
Sarab	− 0.358	− 0.445	− 0.003	− 0.052	− 0.060	0.137	0.002	− 0.783	− 1.336	− 1.509
Sarakhs	0.014	− 0.498	− 0.019	0.005	0.026	− 0.161	− 0.024	0.095	0.184	− 0.823
Saravan	0.272	0.912	0.027	− 0.090	− 0.021	2.611	0.045	0.762	0.876	− 1.088
Sarpol-e Zahab	− 1.091	− 0.999	− 0.068	− 0.284	− 0.191	0.536	− 0.039	− 2.968	− 2.518	− 9.075
Semnan	0.075	− 0.312	− 0.023	− 0.029	0.004	1.183	0.001	0.237	0.353	− 0.870
Shahrekord	0.131	− 0.319	0.036	− 0.016	0.015	0.761	− 0.019	0.365	0.475	− 1.265
Shahrood	− 0.098	− 0.409	− 0.015	− 0.058	− 0.010	0.317	− 0.013	− 0.442	− 0.655	− 1.327
Sharghe Isfahan	− 0.076	− 0.21	0.015	0.005	− 0.012	0.681	0.009	− 0.119	− 0.019	− 0.313
Shiraz	0.066	0.416	0.076	− 0.051	0.036	− 0.276	− 0.037	1.994	− 0.426	− 0.732
Sirjan	− 0.371	− 1.237	− 0.005	− 0.066	− 0.046	1.311	− 0.039	− 1.654	− 0.595	− 2.172
Tabas	− 0.243	− 0.23	− 0.030	− 0.070	− 0.030	− 0.752	− 0.013	− 0.963	− 0.428	− 1.032
Tabriz	− 0.275	− 0.257	0.014	− 0.046	− 0.027	0.648	− 0.039	− 0.073	0.055	− 3.346
Takab	− 0.558	− 1.46	− 0.054	− 0.374	− 0.116	1.279	− 0.110	− 4.050	− 1.996	− 9.175
Tehran	− 0.084	− 0.373	− 0.008	− 0.002	0.000	− 0.605	0.027	− 0.087	0.120	− 1.187
Torbat Heydariyeh	− 0.3	− 0.248	− 0.027	− 0.113	− 0.046	0.309	− 0.031	− 0.978	− 0.087	− 3.212
Zabol	− 0.28	− 0.441	− 0.037	− 0.027	− 0.015	0.800	− 0.017	− 0.615	− 0.541	− 1.154
Zahedan	0.032	0.258	− 0.013	− 0.022	0.002	1.692	0.017	0.036	0.286	− 0.728
Zanjan	− 0.095	− 0.205	− 0.009	− 0.027	− 0.017	0.764	− 0.042	− 0.387	− 0.127	− 2.650
Average	− 0.19	− 0.42	− 0.01	− 0.12	− 0.04	0.50	− 0.03	− 0.72	− 0.22	− 3.52
Stations having positive trend	19	16	27	11	19	53	15	24	31	7
Stations having negative trend	57	60	49	65	54	23	61	52	45	69
Stations having no trend	0	0	0	0	3	0	0	0	0	0

Italic numbers denote statistically significant trends at 5% critical level

the diurnal temperature range (DTR) was observed at 37 stations (17 statistically significant), as well as the increasing trend at 30 stations (20 statistically significant). In this respect, stations having significant negative trends are mostly observable in the northern and central parts as well as in the Persian Gulf and Oman Sea coasts of the country and those indicating significant positive trends are observed in the northwest (Fig. 6). In parallel with the results of the IPCC (2007), an increase (decrease) in the WSDI (CSDI) is observed across large parts of the country, consistent with the results of Rahimzadeh et al. (2009); in addition, Mohan et al. (2020) reported that the DTR has had significant decreasing trends since the nighttime temperatures have risen, but the daytime temperatures have not significantly fallen for Barbados, a Caribbean island.

3.2 Precipitation-related indices

Table 4 presents the results of trend analysis and their estimated slopes for the trend line of the precipitation-related indices presented in Table 2 for all selected stations throughout Iran. The italic numbers in the table denote statistically significant trends detected by the Mann-Kendall trend test at the 5% critical level. In the table, a decreasing trend is shown in the cases of the monthly maximum 1-day precipitation (RX1day) for 57 stations at an average rate of − 1.9 mm/decade. Figure 7 a shows that most stations located in the northern half of the country showed a decreasing trend, while stations mostly located in the central and the southeastern parts have an increasing trend. Regarding the monthly maximum consecutive 5-day precipitation (RX5day), results showed a negative trend
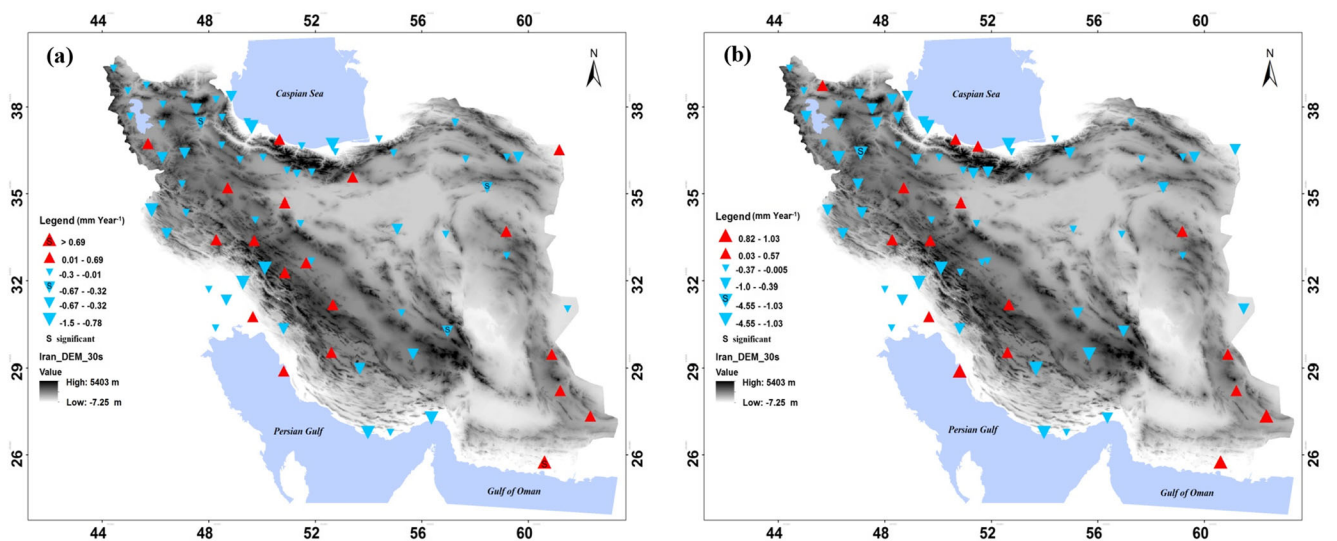
Fig. 7 Trends in monthly maximum **a** 1-day precipitation (RX1day) and **b** consecutive 5-day precipitation (RX5day) (the red up-pointing and turquoise down-pointing triangles designate the increasing and decreasing trends, respectively)

at 60 stations mainly situated in the western half of Iran that are mostly insignificant at −4.2 mm/decade on average (Fig. 7b).

According to Rahimzadeh et al. (2009), Iran's central, eastern, and northeastern areas experiencing heavy rainfall in recent years showed a decreasing trend in both RX1day and RX5day. Asgari et al. (2008) reported that the precipitation-related indices in most of the stations have a decreasing trend. The outcomes of the present study confirm the results of these two studies. Despite recent years' severe droughts in the southeast, the trend of changes in the two indices mentioned above is positive, inconsistent with the results of both Asgari et al. (2008) and Rahimzadeh et al. (2009). This issue can be due to an increase in the maximum daily rainfall of 5 days and RX5day between 2003 and 2010, especially during the period

2008–2009, when the widespread droughts occurred as reported by Raziei et al. (2009), Yazdani and Haghsheno (2008), and Soleimani et al. (2005).

The number of heavy precipitation days (R10) and very heavy precipitation days (R20) decreased by −1.2 and −0.4 day/decade, as observed on average, respectively, at 65 and 54 out of 76 stations (15 and 7 statistically significant). Figure 8 illustrates that stations mainly located in the northwest and west have the most intensely negative trend for both indices. These findings agree with the results of Rahimzadeh et al. (2009) and Babaei et al. (2014).

In the very wet days (R95p) and extremely wet days (R99p) indices (i.e., annual total PRCP when RR > 95th and 99th percentile), decreasing trends were observed at 52 and 45 stations by −7.2 and −2.2 mm/decade on average,
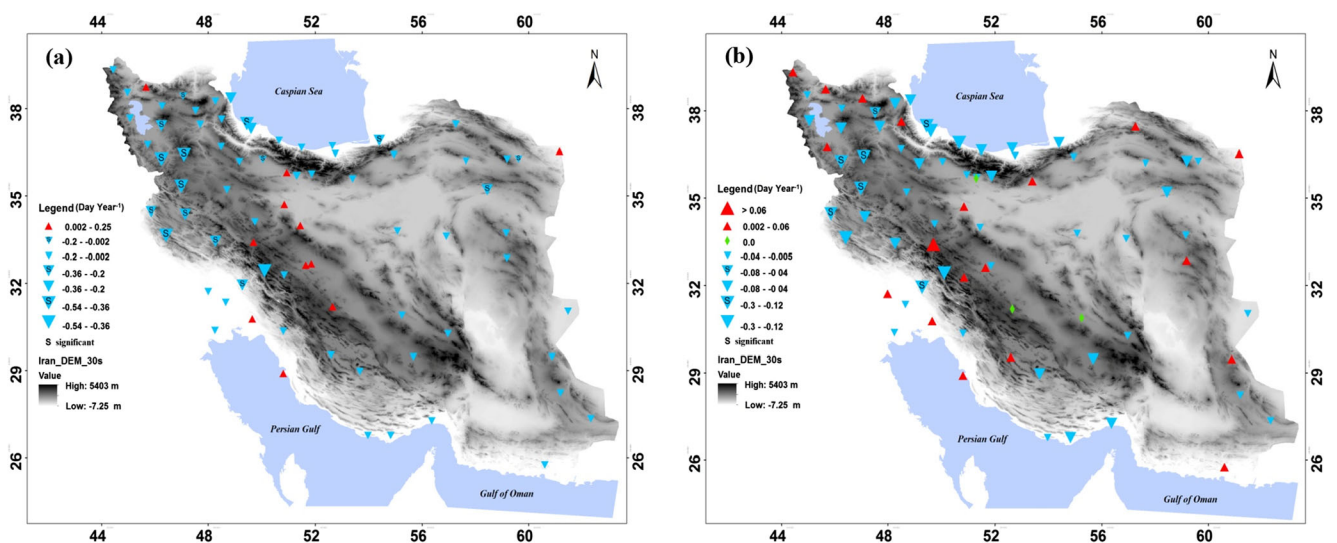
Fig. 8 Trends in number of **a** heavy precipitation days (R10) and **b** very heavy precipitation days (R20) (the red up-pointing and turquoise down-pointing triangles designate the increasing and decreasing trends, respectively)
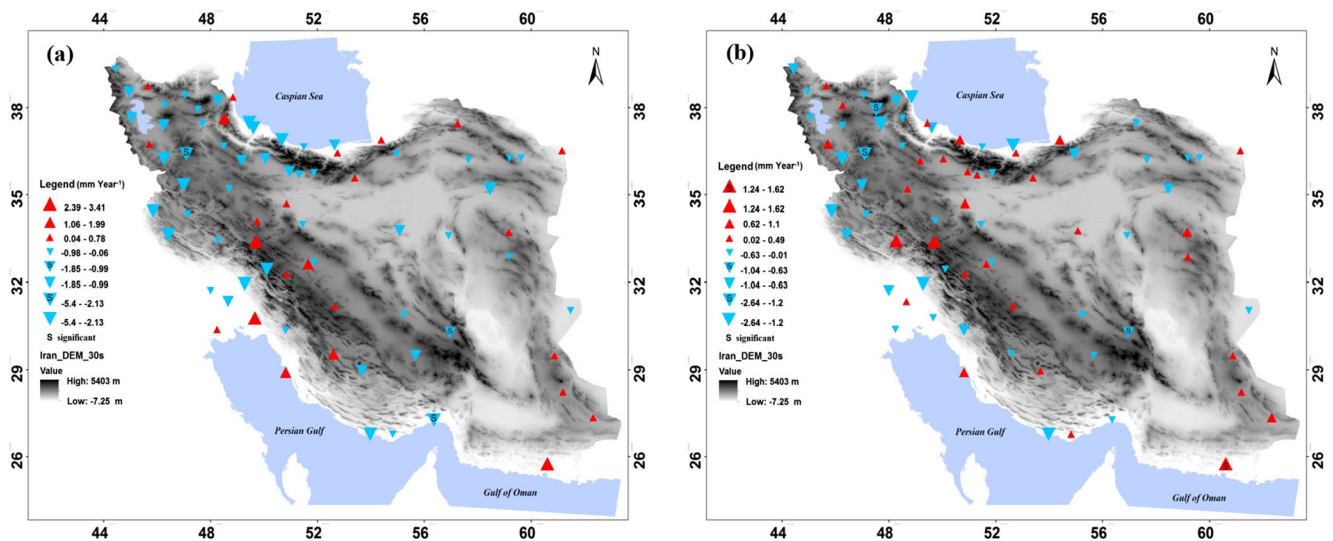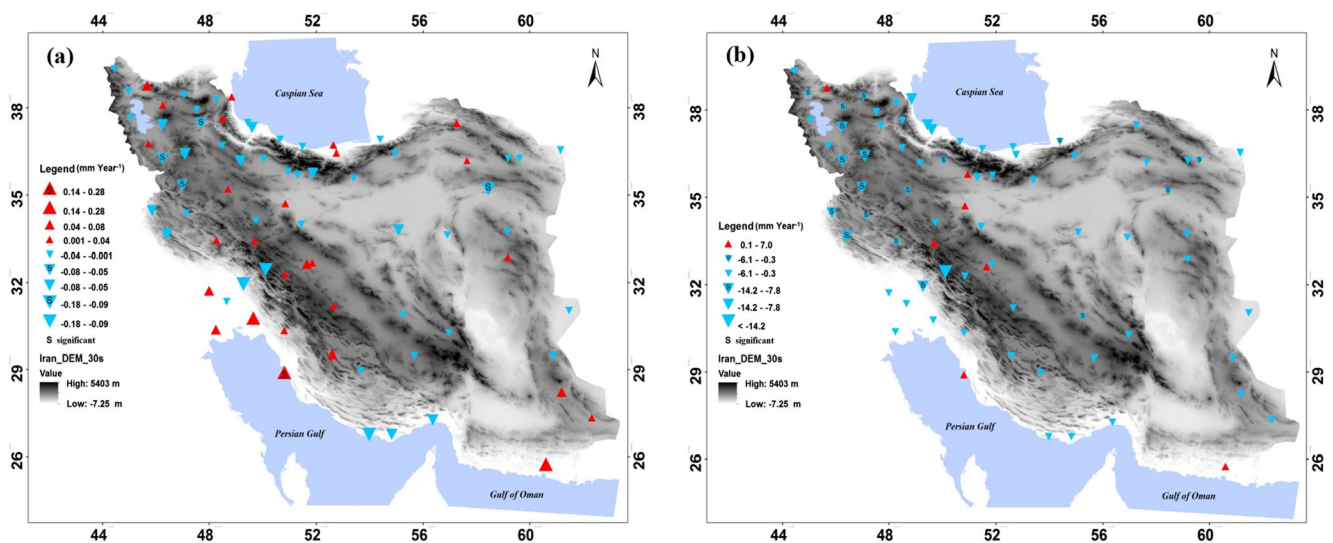
Fig. 9 Trends in **a** very wet days (R95p) and **b** extremely wet days (R99p) (the red up-pointing and turquoise down-pointing triangles designate the increasing and decreasing trends, respectively)

respectively. Figure 9 shows that the stations chiefly located in the west have more trend slope than others in both indices. According to Rahimzadeh et al. (2009) and Asgari et al. (2008), the northwest and west showed a sharply decreasing trend in both R95p and R99p, which our study confirms.

In the annual precipitation indices, statistically negative trends predominated in the simple daily intensity index (SDII) and the annual total wet-day precipitation (PRCPTOT). In the case of the SDII, 49 out of 76 stations (4 statistically significant) showed the decreasing trends at an average rate of −0.1 mm/decade throughout the nation (Fig. 10a). For the PRCPTOT, 69 stations (18 statistically significant) situated in the northwest and west reported average declines of −3.52 mm/year, and also showed negative trends (Fig. 10b). The present study's results of the

PRCPTOT index agree with the studies by Rahimzadeh et al. (2009), Asgari et al. (2008), and Babaei et al. (2014), which specified a decreasing trend in PRCPTOT in the west and northwest. Tabari and Hosseinzadeh Talaee (2011) reported that approximately 60% of meteorological stations had a decreasing trend in precipitation for the period 1966–2005, most located in the west. The number of consecutive dry days (CDD) increased at 53 stations by 5 days/decade on average. Rahimzadeh et al. (2009) presented changes in the CDD with a decreasing trend in most regions. Most stations located in the north, northwest, and east showed a positive trend in the CDD (Fig. 11a), agreeing with Rahimzadeh et al. (2009) and confirming a positive trend in this index in the north. The results concerning the number of consecutive wet days (CWD) index showed a decrease at 59 stations (8

Fig. 10 Trends in **a** simple daily intensity index (SDII) and **b** annual total wet-day precipitation (PRCPTOT) (the red up-pointing and turquoise down-pointing triangles designate the increasing and decreasing trends, respectively)
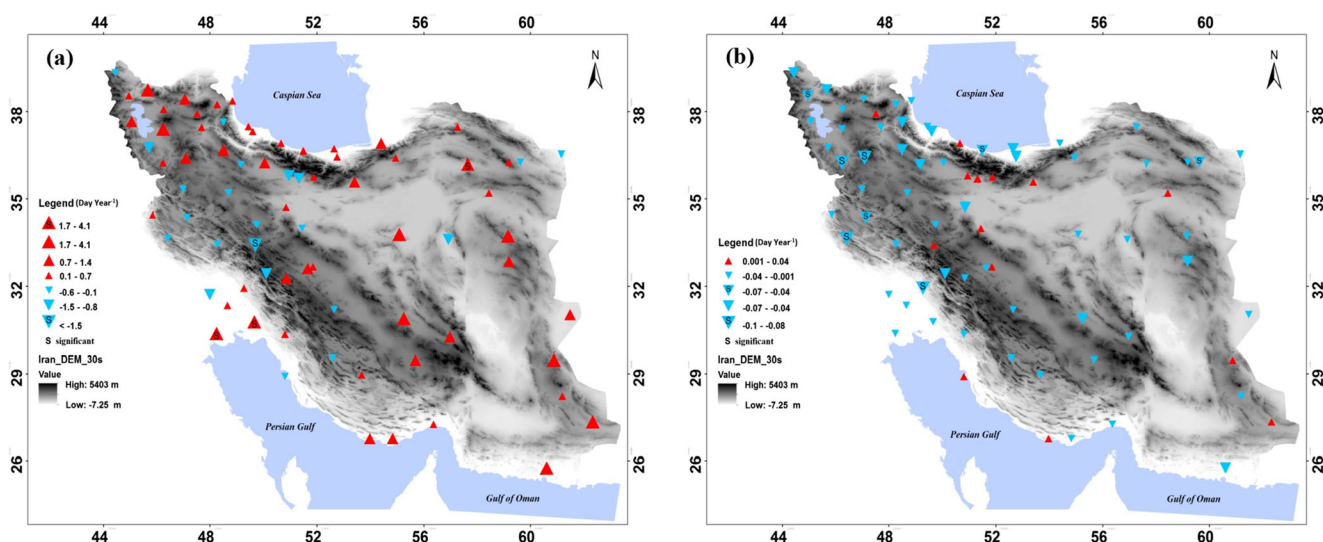
Fig. 11 Trends in number of consecutive **a** dry days (CDD) and **b** wet days (RR ≥ 1 mm, CWD) (the red up-pointing and turquoise down-pointing triangles designate the increasing and decreasing trends, respectively)

statistically significant) by − 0.3 day/decade on average. Geographically, stations with a negative trend in the CWD were located mostly in the western half of the country, while stations indicating a positive but insignificant trend are situated throughout Iran (Fig. 11b).

4 Conclusion

The present study was designed to identify the changes and trends in climate extremes throughout Iran using precipitation- and temperature-related extreme indices for the period 1981–2010. Assessment of temperature-related extreme indices showed that temperature overall had an increasing trend throughout the country over the study period. The maximum and minimum values of daily maximum and minimum temperatures demonstrated an increasing trend in most regions. In addition, the increasing trends in the number of warm days and nights were observed at most stations, such that nearly 80% of the stations showed significant trends. Concerning the number of cool days and nights, a decreasing trend was observed at most stations, and about 70% of the stations had significant trends. Additionally, the trend in warm spell duration at most stations increased, showed a significant trend at more than 50% of the stations. Cold spell duration declined significantly in most parts of the country, in over 30% of the stations. Spatial analysis revealed that the increasing trend in temperature for the northwest and west was more noticeable than that of the other regions; the stations there evidenced more severe trends. Precipitation declined over a large part of Iran during 1981–2010, so virtually all precipitation-related extreme indices showed a decreasing trend at most stations. The exception was the CDD that indicated an increasing trend at most stations. More than 90% of the stations

showed a decreasing trend in the PRCPTOT index, and in almost 26% of them, the trend was significant. Although most of the stations did not show significant trends in precipitation-related indices, the stations located in the west and northwest exhibited a significant negative trend.

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