Trend analysis of climate change compound indices in Iran

Ahmad Roshani, Fatemeh Parak and Hossein Esmaili

ABSTRACT

The time-placement scheme of climate extreme changes is important. In this regard, a set of a compound indices derived using daily resolution climatic time series data is examined to assess climate change in Iran. The compound indices were examined for 47 synoptic meteorological stations during 1981–2015. The results show that most stations experienced a negative trend for the cool/dry (*CD*) and cool/wet (*CW*) index and a positive trend in *CW* was observed in some dispersed small areas. Both warm/dry (*WD*) and warm/wet (*WW*) indices have similar behavior, but the magnitude and spatial consistency of *WW* days were much less than *WD* days. The results show that more than 80% of stations experienced a decrease in the annual occurrence of the cold modes and an increase in the annual occurrence of the warm modes. On the other hand, universal thermal climate index (*UTCI*) change demonstrated a significant increase in the annual occurrence of strong heat stress (32–38 °C) and significant decrease in the annual occurrence of no thermal stress class (9–26 °C). Moreover, trends in tourism climate index (*TCI*), including $TCI \geq 60$ and $TCI \geq 80$, showed similar changes but with weak spatial coherence.

Key words | climate change, compound index, Iran, Mann–Kendall test, statistical trend

Ahmad Roshani (corresponding author)
Department of Remote Sensing,
Islamic Azad University,
Tehran North Branch, Tehran,
Iran
E-mail: *ahmadroushani@gmail.com*

Fatemeh Parak
Department of Geography,
Farhangian University,
Tehran,
Iran

Hossein Esmaili
Department of Geography,
Kharazmi University,
Tehran,
Iran

INTRODUCTION

Climate change is considered as a global challenge whose effects differ by region and local characteristics (Leonard *et al.* 2014; Filho *et al.* 2016). During the past decades, large positive temperature increases from their mean values have become common in many parts of the world. In both hemispheres, the land surface temperature has increased at a faster rate than the oceans according to the Intergovernmental Panel on Climate Change (IPCC 2007). The Earth's surface temperature has maximized over the last three decades and has seen increasing trends since 1850. In this regard, the northern hemisphere has become much warmer from 1983 to 2012 than any 30-year period in the last 1,400 years. The linear trends of the average land and ocean surface combination temperature data during the period 1880 to 2012 reveal an increase of about 0.85 °C (IPCC 2013). The planning and performance of human community infrastructures in relation to food, water, energy, shelter, and transportation depend on climate extreme change values according to the World Meteorological Organization (WMO 2009). The economic changes and the effects of extreme climate change are among the most important challenges humans face regarding climate change, states the Climate Change Science Program (CCSP 2008). The latest outputs of meteorological models suggest that global warming has caused an increase in evaporation from land surface and surface water bodies, which is anticipated to have a serious impact over time on water resources management and the global population (Moazenzadeh *et al.* 2018). Meanwhile, global warming has caused increasing and several climate events such as drought, heat waves, floods, and fires in different parts of the world (Alexander *et al.* 2006; Aghakouchak *et al.* 2014; Leonard *et al.* 2014). Predicting climate extremes based on temperature and precipitation index in the Fifth Report of the

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IPCC highlights a significant growth in the number and magnitude of warm and dry periods (Hao *et al.* 2013; Filho *et al.* 2016). The daily index consists of temperature or precipitation extremes which have been used for assessing long-time variability and frequency of days above or below specific physically based thresholds (Zhang *et al.* 2011). Mainly, due to the interdependence and thermodynamics, relations between precipitation and temperature have been addressed in numerous studies (Liu *et al.* 2012). The main goal of analyzing extremes is to describe the balance and changes of climate to find the most desirable balance in macro plans for applying high safety standards and preventing great loss to communities and systems with regard to severe events. Sometimes, one variable may be in an extreme state, but more often, these events can be considered as a combination of variables, not all of which are necessarily extreme (Leonard *et al.* 2014). An extreme impact may be a combination of one or more variables leading to a severe change in climate, referred to as a compound event. According to copula theory (Miao *et al.* 2016), recent studies have been conducted based on describing the compound index of climate combinations as warm/dry, warm/wet, cool/dry, and cool/wet (Lopez-Moreno *et al.* 2011; Estrella & Menzel 2012; Arsenovic *et al.* 2013; Hao *et al.* 2013). These compound indices reveal the change at all spatial or temporal scales with significant trends in the frequency of the cool and warm modes.

Most parts of Iran are located in the desert belt, which is affected by extreme climate change and trends. Therefore, considering trends and climate change and their effects is essential and unavoidable for planning risk management in relation to communities, systems, and infrastructures through adaptation and the bad effects of climate change. Several national studies have investigated trends of climatic variables in Iran. In recent studies, several extreme precipitation and temperature indices have been analyzed (Rahimzadeh *et al.* 2009; Tabari *et al.* 2011; Parak *et al.* 2015), but the climate change was not concerned with the use of compound extreme indices. These studies provided important findings, although they have focused on only the individual elements of the climate and have used mean and extreme values of climate variables. This paper is one of the first national studies to be based on compound values. In this study, the composition of more different climatic elements is considered and several statistical tests were used for trend detection. The main purpose of this paper is to demonstrate the trend of compound indices in order to find the impact of climate change over the study area. In this regard, the trends of combined temperature, precipitation, humidity, wind speed, and sunshine statistics in a spatial domain in Iran are investigated as the main research objectives. The aim of the present research was to understand the variations in compound values of temperature and precipitation and other variables. Compared to previous studies, this can provide a comprehensive view of the behavior of the cool and warm modes of heat and moisture, of which analysis of the statistics of each variable is taken individually.

DATA AND METHODS

Iran is the spatial domain used in this study (latitude 25–40 and longitude 44–64). The total area is 1,648,000 km^2 and it includes a population of about 75 million, according to the latest National Census of Iran. The climate of Iran varies due to differences in latitude, altitude, and a range of geographic features, including mountains and deserts. Currently, daily data are available for more than 150 synoptic stations in Iran, but there are long-term records for only a few stations. Most of the stations, especially in the earlier years, contain inhomogeneities and uncertainties in their data sets. Our study was limited to only 45 stations, due to the problems mentioned above, or to the presence of wide data gaps, and also to the shortness of record length. On the other hand, the data after 2015 have either been unverified or are not available. The selected stations take into account the length and completeness of records. In order to interpret the climate change compound index, the data were collected from 45 synoptic stations in Iran for the period 1981–2015. These stations have long-time data and are well distributed in different climate regions and elevation levels. The data have been obtained from Iran Meteorological Organization (*IRIMO*) (Figure 1 and Table 1).

Methodology

Data quality and homogeneity

Due to the importance of climate change studies, the *WMO* focuses on quality control and data homogeneity (WMO

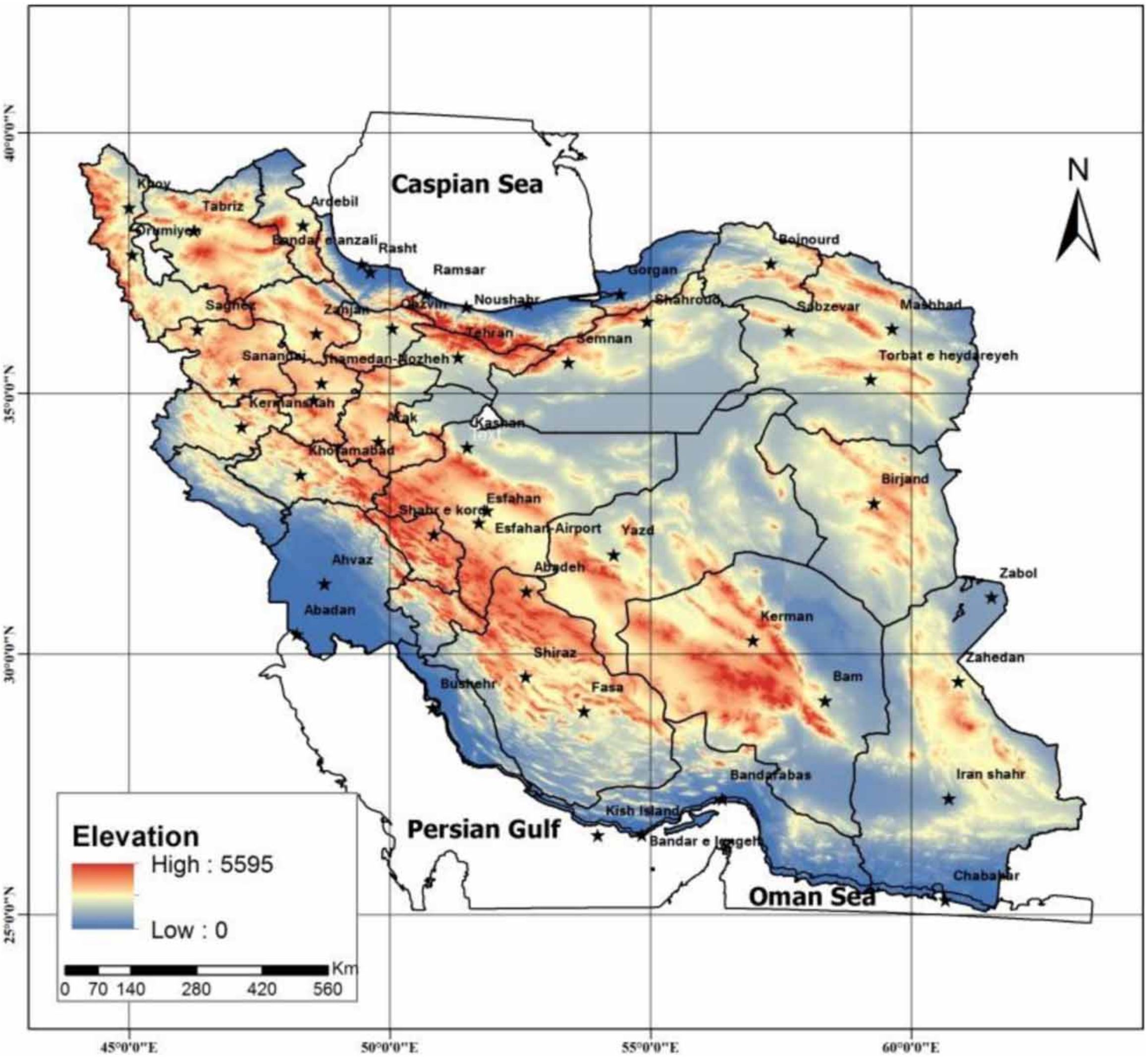

Figure 1 | Geographical positions of the 47 synoptic stations over Iran.

2009). One of the most important factors of data inhomogeneity is the change in observation, including time of observation and tools, change of station location, formula, and change in data processing (WMO 2011). Studies of extreme index in climate change have been carried out based on meteorological observation in Iran. As they have errors and uncertainty (Rahimzadeh *et al.* 2009), so the climatic series have inhomogeneity with sudden and abnormal spikes and deviations and unreal interpretation of climate change. The objective of quality control is to verify whether a reported data value is representative of what was intended to be measured and has not been contaminated by unrelated factors. In this study, *ClimPACT* software, available as Free Software, is undertaken as the main tool for data analysis. This software is written in *R*, a language and environment for statistical computing and graphics, and developed by the *WMO* Expert Team on Climate Change Detection and Indices. First, the *ClimPACT* quality control (*QC*) revealed unreasonable values of temperature and precipitation data, such as daily precipitation amounts less than zero and daily maximum temperature less than daily minimum temperature. In addition, the *QC* also identified outliers in daily maximum and minimum temperatures. It is worth mentioning that all potential data can be evaluated by information on the next and previous day of the event with specialized knowledge about local

Table 1 | Summary of the characteristics and details of the selected synoptic stations

Station	Height (m)	Type of climate	Station	Height (m)	Type of climate	Station	Height (m)	Type of climate
Abadan	6.6	BWh	Bushehr	9	BSh	Shahrud	1,325.2	BWk
Arak	1,702.8	DCsa	Tabriz	1,361	BSk	Shahrekord	2,048.9	DCsa
Ahvaz	22.5	BSh	Tehran	1,191	BSh	Shiraz	1,488	Csa
Esfahan	1,550.4	BWh	Torbat-e Heydariyeh	1,451	Doa	Qazvin	1,279.1	Doa
Orumiyeh	1,328	DCsa	Khorramabad	1,147.8	Csa	Gorgan	0	Csa
Bandar-e-Anzali	−23.6	Cfa	Khoy	1,103.4	BSk	Kerman	1,754	BWh
Babolsar	−21	C	Ramsar	−20	Cfa	Kermanshah	1,318.5	Doa
Bam	1,066.9	BWh	Rasht	−8.6	Cfa	Mashhad	999.2	BSk
Bandarabbas	9.8	BWh	Zahedan	1,370	BWh	Yazd	1,230.2	BWh
Birjand	1,491	BSh	Zabol	489.2	BWh	Hamedan	1,679.7	DCsa
Khodabandeh	1,659.4	DCsa	Hamedan	1,740.8	DCsa	Fasa	1,268	Csa
Sabzevar	972	BSh	Ardebil	1,335.2	DCsb	Esfahan	1,551.9	BWk
Sanandaj	1,373.4	Doa	Nowshahr	−20.9	Cfa	Abadeh	2,030	BSk
Saghez	1,522.8	DCsa	Semnan	1,127	BWh	Kish Island	30	BWh
Chahbahar	8	BWh	Kashan	955	BWh	Bandar-e-Lengeh	22.7	BWh
Bojnurd	1,065	BSk	Iranshahr	591.1	BWh			

conditions. The *QC* test of other climatic variables such as humidity, sunshine, and wind speed was done using simple statistical methods in *SPSS* software.

There are several methods for the assessment of homogeneity in time series data including relative and absolute methods. The relative tests are standard normal homogeneity test and, more reliably, it is recommended that the test is conducted by correlating the test data series with the homogeneous data series of a neighboring station (Tayanç *et al.* 1998; Wijngaard *et al.* 2003; Tsidu 2012). The research uses the R homogeneity test (*RH-test*) V5 software (Wang & Feng 2013) by using the penalized maximal *F-test* (*PMF*) methods to check the homogeneity of the monthly temperature and precipitation and other variables' meteorological data. The software method is based on the *PMF* or *F-test* and can identify, and adjust for, multiple change points in a time series (Wang 2008). The *F-test* is a relative test for structural breaks with reference series, namely multiple change point detection method, and the RH-test has the best detection rate (Yozgatligil & Yazici 2015). In the case of a lack of reference station, the *F*-test is used for inhomogeneity detection in time series (Wang *et al.* 2007; WMO 2011; Vincent *et al.* 2012; Fan & Chen 2016). *PMF* requires the use of reference stations for the homogeneity analysis, but *PMF* can be used as an absolute method (i.e., when there are no neighbouring stations to use for comparison). According to the diagrams, if any heterogeneous factors are identified, the time series is assumed to be inhomogeneous, otherwise the time series is homogeneous.

Compound index

The aim of the indicators is to illustrate the temporal and spatial distribution of climate change. It is important to develop a set of compound indices that are statistically robust to cover a wide range of climates and detect changes in climate extremes. Combined indices and heat wave indices are a set of statistical indices that can cover a wide range of climate characteristics and detect variability and changes in climate. In other words, most extreme weather events are the result of combining climate variables. For example, high temperatures coupled with reduced rainfall can cause heat waves and droughts (Klok & Klein Tank 2008). Therefore, following annual study, a specified compound extreme index consisting of seven indices was considered as specified in Table 2.

Table 2 | List of the ECA&D (2013) climate index

No.	Index	Definition	Unit
1	*CD*	Days with $TG < 25th$ percentile of daily mean temperature and $RR < 25th$ percentile of daily precipitation sum (cold/dry days)	Days
2	*CW*	Days with $TG < 25th$ percentile of daily mean temperature and $RR > 75th$ percentile of daily precipitation sum (cold/wet days)	Days
3	*WD*	Days with $TG > 75th$ percentile of daily mean temperature and $RR < 25th$ percentile of daily precipitation sum (warm/dry days)	Days
4	*WW*	Days with $TG > 75th$ percentile of daily mean temperature and $RR > 75th$ percentile of daily precipitation sum (warm/wet days)	Days
5	*UTCI*	Mean of the universal thermal climate index	°C
6	*TCI60*	Days where the tourism climatic index _ 60	Days
7	*TCI80*	Days where the tourism climatic index _ 80	Days

All indices are calculated annually.

As illustrated in Table 2, the combination of the precipitation and temperature quantities represent the four climate combinations: cool/dry (low temperature and low precipitation), cool/wet (low temperature and high precipitation), warm/dry (high temperature and low precipitation), and warm/wet (high temperature and high precipitation). The 10 and 90 percent quantities define an extreme event, according to an *IPCC* report (2007) and the 25% and 75% values of precipitation and temperature are used as threshold levels for defining the compound extremes of temperature and precipitation in order to capture a large number of events.

Another compound index, which was used in this study, is the *UTCI*. The scale of the index is able to express even slight differences in the intensity of meteorological stimulus. The assessment of the thermo-physiological effects of the atmospheric environment is one of the key issues in human biometeorology. To quantify these effects, the *UTCI* is developed in Cooperation in Scientific and Technical Research (COST) action 730. The main aim of the index is to present an environmental-physiological evaluation model to increase the plans related to health and welfare in public climate service, public health systems, prevention designs, and climate effects research (Broede *et al.* 2012).

In order to calculate *UTCI*, the data of average wind speed, relative humidity, and sunshine duration and mean radiant temperature (*MRT*) were used. Sunshine duration was used to estimate direct solar radiation (R_s) (which is required as input to the mean radiant temperature) and relative humidity was used to estimate water vapor pressure based on daily maximum and minimum temperature values (Lemke & Kjellstrom 2012). *MRTs* were calculated from air temperature, global temperature, and wind speed.

To calculate the global temperature, first we need to have R_s. If R_s is unknown, it can be calculated with the angstrom formula (1):

$$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a \tag{1}$$

where no actual solar radiation data are available and no calibration has been carried out, for improved a_s and b_s parameters, the values of 0.25 and 0.50 are recommended, respectively, by the Food and Agricultural Organization of the United Nations (Allen *et al.* 1998). Here n is actual duration of sunshine [hour] and N is maximum possible duration of sunshine of daylight hours [hour]. Maximum possible duration of sunshine, N, and the sunset hour angle, ω_s, are calculated from Equations (2) and (3), respectively:

$$N = \frac{24}{\pi} \omega_s \tag{2}$$

$$\omega_s = across[-\tan(\varphi) tan(\delta)] \tag{3}$$

The latitude, φ expressed in radians is considered positive for the northern hemisphere and negative for the southern hemisphere. The conversion from decimal degree to radians and the solar declination, δ, are given by:

$$\varphi = \frac{\pi}{180} [decimaldegrees] \tag{4}$$

$$\delta = 0.409 sin\left(\frac{2\pi}{365}\right) J - 1.39 \tag{5}$$

The extraterrestrial radiation, R_a, for each day of the year and for different latitudes can be estimated from the solar constant, the solar declination, and the time of the year by:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi)\, sin(\delta) + \cos(\varphi)\, cos(\delta)\, sin\,(\omega_s)] \tag{6}$$

where G_{sc} solar constant equals to 0.0820 MJ m^{-2} min^{-1}, and the inverse relative Earth-Sun, d_r, is calculated from Equation (7):

$$d_r = 1 + 0.033cos\left(\frac{2\pi}{365}J\right) \tag{7}$$

Mean radiant temperature (*MRT*) calculated from Equation (8) is:

$$MRT = [(GT + 237)^4 + 2.5 \times 10^8 \times v^{0.6}(GT - Ta)]^{1/4} \tag{8}$$

For converting the relative humidity to vapor pressure carried out based on Brice & Hall (2013) (Equation (9)):

$$\text{P}\ (hPa) = RH/100 \times 6.105exp(17.27Ta/(237.7 + Ta)) \tag{9}$$

Use this empirically derived formula for *GT* (Equation (10)):

$$GT(^\circ C) = Ta + 0.0175SR - 0.208_V \tag{10}$$

Finally, *UTCI* is computed by the regression equation found at www.UTCI.org. The rating categories of the *UTCI* are shown in Table 3.

The tourism climatic index (*TCI*) represents a quantitative evaluation of world climate for tourism purposes and is an absolute measure of the climatic well-being of tourists. The *TCI* is aimed at tourists involved in sight-seeing or light outdoor activities. The *TCI* was originally defined by Mieczkowski (1985) as a weighted sum of several factors. *TCI* is calculated according to Equation (11):

$$TCI = 2(4CID + CIA + 2R + 2S + W) \tag{11}$$

where *CID* is a daytime comfort index, consisting of the mean maximum air temperature (°C) and the mean minimum relative humidity *RH* (%), *CIA* is the daily comfort index, consisting of the mean air temperature (°C) and the mean relative humidity (%), *R* is the precipitation (*mm*), *S* is the daily sunshine duration (*h*), and *W* is the mean wind speed (*m/s*). Due to the weighting factor (a value for *TCI* of 100), every factor can reach 5 points. The value of the *TCI* varies between 100 (ideal) to <10 (impossible). The rating categories of *TCI* are shown in Table 4.

Table 3 | *UTCI* equivalent temperature and stress category (Pappenberger et al. 2015)

UTCI (°C) range	Stress category
>46	Extreme heat stress
38–46	Very strong heat stress
32–38	Strong heat stress
26–32	Moderate heat stress
9–26	No thermal stress
0–9	Slight cold stress
0 to −13	Moderate cold stress
−13 to −27	Strong cold stress
−27 to −40	Very strong cold stress
<− 40	Extreme cold stress

Mann–Kendall test

In order to study the trend in time series, the Mann–Kendall test is used assuming the rejection of 'lack of trend in time series'. The nonparametric Mann–Kendall test was developed by Mann (1945) and Kendall (1962) based on data

Table 4 | Classification scheme for the tourism climatic index (Mieczkowski 1985)

TCI range	Description
90–100	Ideal
80–89	Excellent
70–79	Very good
60–69	Good
50–59	Acceptable
40–49	Marginal
30–39	Unfavorable
20–29	Very unfavorable
10–19	Extremely unfavorable
<10	Impossible

ranking in time series not following a certain statistical distribution (Partal & Kahya 2006; Modarres & da Silva 2007; Yue et al. 2002). The test is suitable for data that do not follow a normal distribution, and supports multiple observations per time series (Kampata et al. 2008). The Mann–Kendall test is given as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_k) \tag{12}$$

$$sign(x_j - x_k) = \begin{Bmatrix} +1 \; if \; (x_j - x_k) > 0 \\ 0 \; if \; (x_j - x_k) = 0 \\ -1 \; if \; (x_j - x_k) < 0 \end{Bmatrix} \tag{13}$$

$$Var\ (s) = \frac{[n(n-1)(2n+5)] - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18} \tag{14}$$

where n is the number of data points, t is the number of ties for i value, and m is the number of tied values. Then, Equations (12) and (13) were used to compute the test statistic Z from the following equation:

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}} & if \; S > 0 \\ 0 & if \; S = 0 \\ \dfrac{S-1}{\sqrt{VAR\ (S)}} & if \; S < 0 \end{cases} \tag{15}$$

A positive value of Z indicates an increasing trend and a negative value indicates a decreasing trend. The null hypothesis, H, that there were no trends in the records is either accepted or rejected depending on whether the computed Z statistic is less than or more than the critical value of Z statistics obtained from the normal distribution table at the 5% significance level (Kampata et al. 2008).

In this paper the trend of compound index changes is computed based on decade. The trend of compound index (yj) can be computed using the least square linear regression equation:

$$y_j = a + 0.1b_j + e_j \; j = 1, \; \ldots, \; n \tag{16}$$

where y_j is the value of index in year j and e_j is a disturbance term (residual) with mean zero. The regression coefficient b gives the change per decade (Kanji 2006).

RESULTS AND DISCUSSION

Common index of temperature and precipitation

Most extreme climate events result from combined climate variables. For instance, high temperature with low rainfall may cause heat waves and drought. The changes in threshold ranges for four precipitations (*CD*, *CW*, *WD*, and *WW*) at Ramsar meteorological station during 1981–2015 show that the possibility of occurrence is different and dry modes have the highest possibilities since 1998 (Figure 2). There is a clear correspondence between temperature and precipitation compound index. There are long-term changes in temperature and rainfall annual series based on field observations in Figures 3–7.

Cold/dry days (CD) and cold/wet days (CW)

The annual trends of *CD* compound index based on temperature and precipitation data in Iran are presented in Figure 3(left). This index has a decreasing trend in most stations. The rate of change in the study period based on location between 1 and 10 days in each decade and 1 and 3 days in each decade is decreasing. Except for 15 cases with significant negative trends ($p < 0.05$) that are mainly located in the northwest, we cannot find significant negative trends for the annual *CD* over the whole country, but the decreasing trends are dominant. The changes depend on the location over the course of 1981–2015 in *CD* mode, and decrease between a large spread of 1–10 days per decade, to a much tighter spread of 1–3 days per decade.

The largest and the smallest significant negative trends of *CD* days occurred in Tabriz station, about (−) 6.5 day per decade and in Abadan station about (−) 3.5 day per decade (Figure 4). Negative trends in *CD* were larger than those in *CW* at most stations. The positive trend in this index was observed in some dispersed small areas (Shahrekord, Sabzevar, Gorgan, Rasht, and Torbat e-heydareyeh stations). The magnitudes of the increasing trends in annual *CD* ranged between (+) 3 days per decade at Shahrekord station and (+) 0.3 days per decade at Sabzevar station.

In some regions, such as Khoramabad and Bojnourd, there are very weak and indiscernible trends. Also, coastal

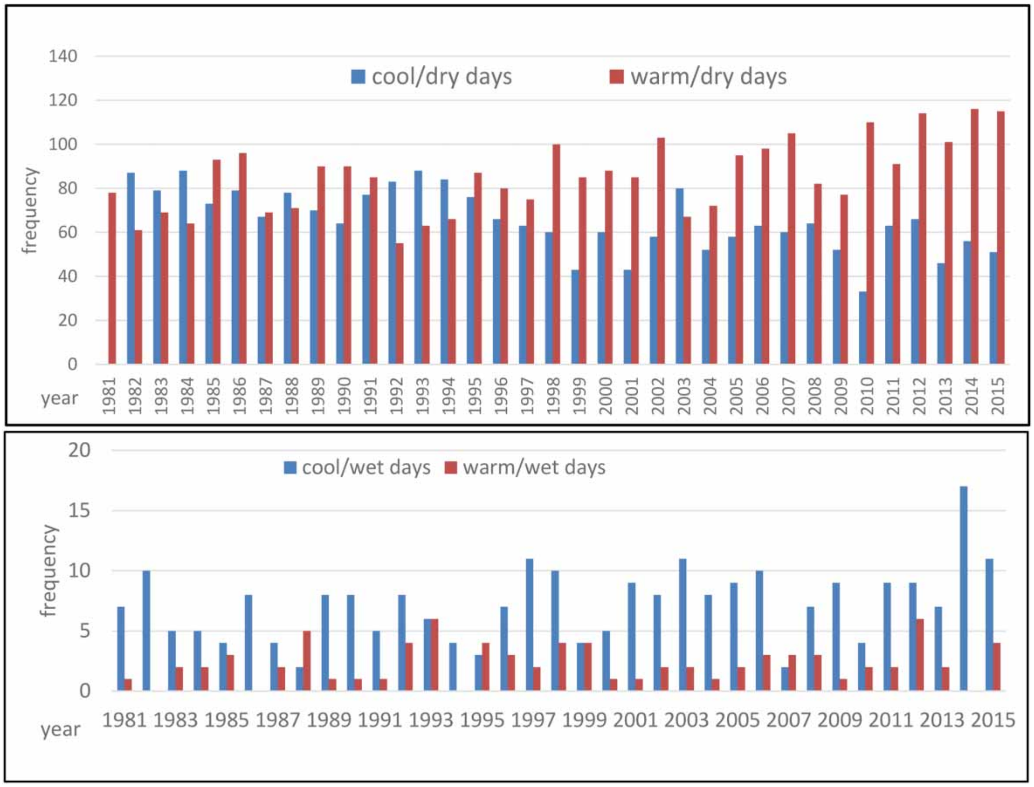

Figure 2 | Threshold exceedance of the four joint temperature and precipitation modes (*CD, WD, CW, WW*) for Ramsar station for the period 1981–2015 [days per years].

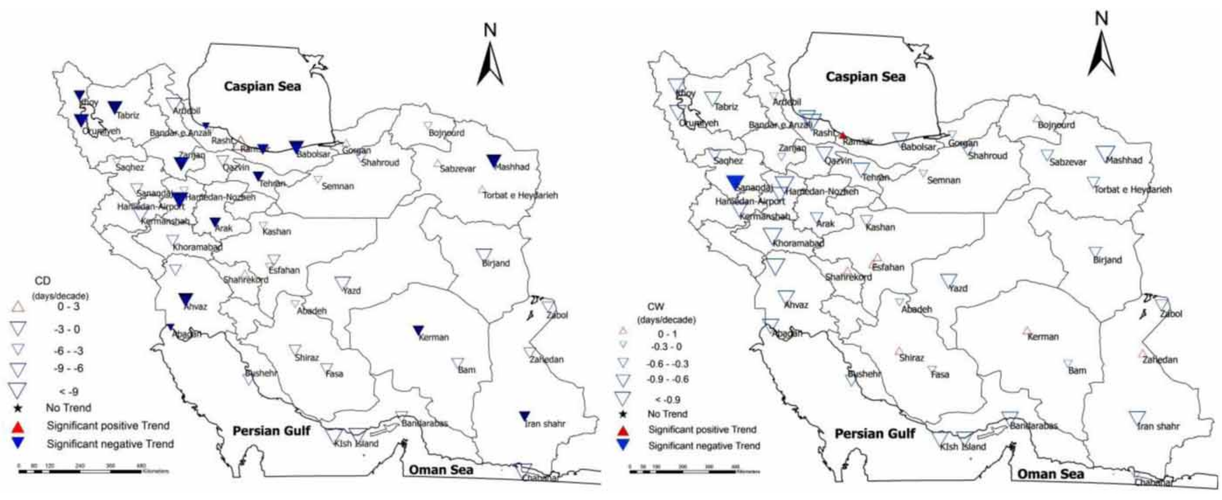

Figure 3 | Decadal trends in the occurrences of the cold/dry extremes (*CD*) (left) and cool/wet extremes (*CW*) (right), for the period 1981–2015 (days/decade).

areas of the Caspian Sea and coastal strips of the Persian Gulf clearly show higher annual *CD* days.

Distinguishable negative trends of annual *CD* were found to be in good agreement with the results obtained for other territories in Europe (Beniston 2009), where a tendency towards colder years has been identified.

The *CW* index is defined as the number of days where *T25/P75*. Here, *T25* indicates temperature occurrences

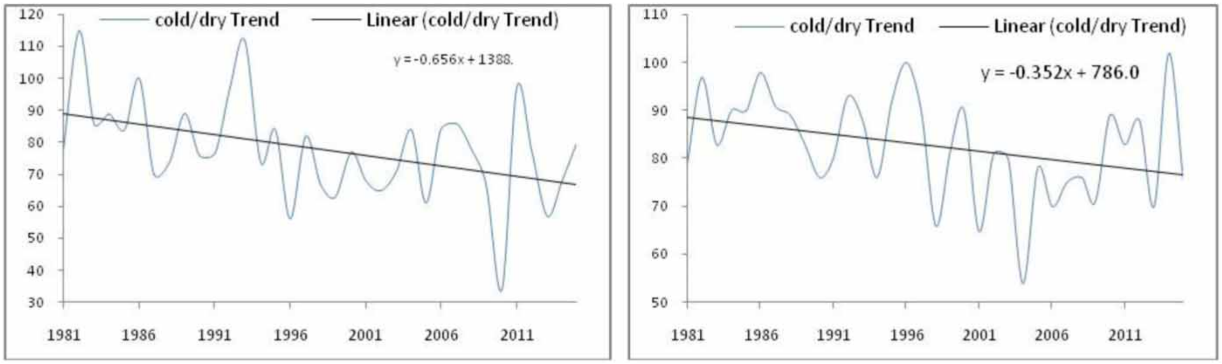

Figure 4 | Time series of the cold/dry (*CD*) extremes for Abadan (right) and Tabriz (left) stations for the period 1981–2015 (days/decade).The solid (dashed) black lines indicate trend lines, and the equations given in the top of each diagram represent specifications of the trends.

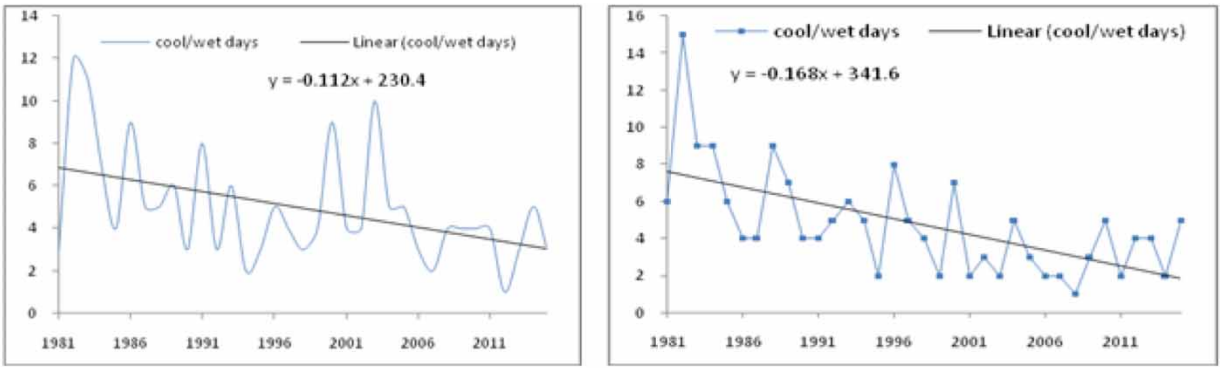

Figure 5 | Time series of the cool/wet (*CW*) extremes for Hamedan (left) and Sanandaj (right) stations for the period 1981–2015 (days/decade). The solid (dashed) black lines indicate trend lines, and the equations given in the top of each diagram represent specifications of the trends.

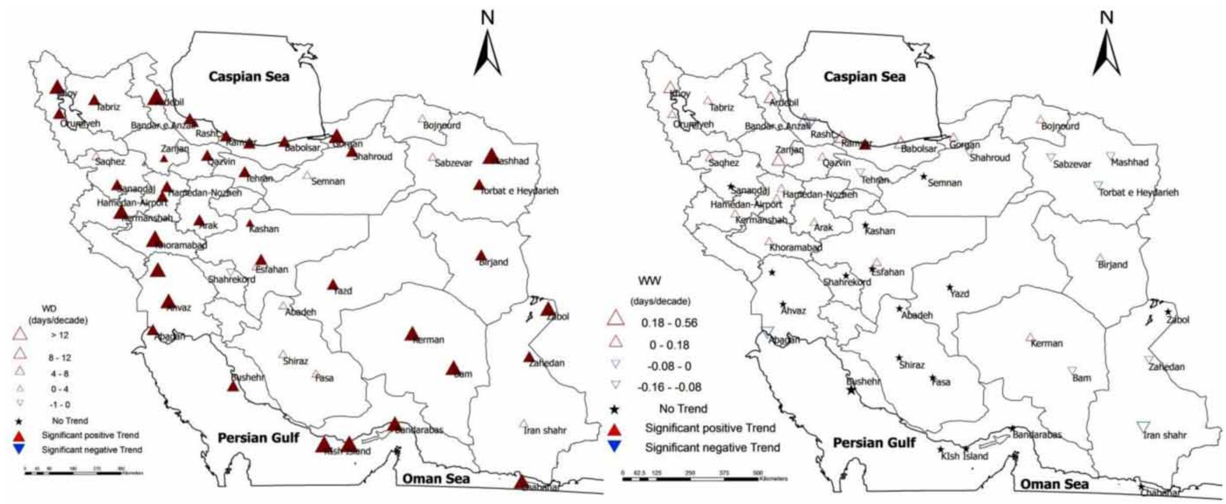

Figure 6 | Decadal trends in the occurrences of the warm/dry (*WD*) (left) and the warm/wet (*WW*) (right) extremes for the period 1981–2015 (days/decade).

below the 25% quantile, while *P75* denotes occurrences above the 75% quantile. The outputs of the statistical tests in the annual *CW* series over the period of 1981–2015 are shown in Figure 3 (right). Except in parts of the south-west

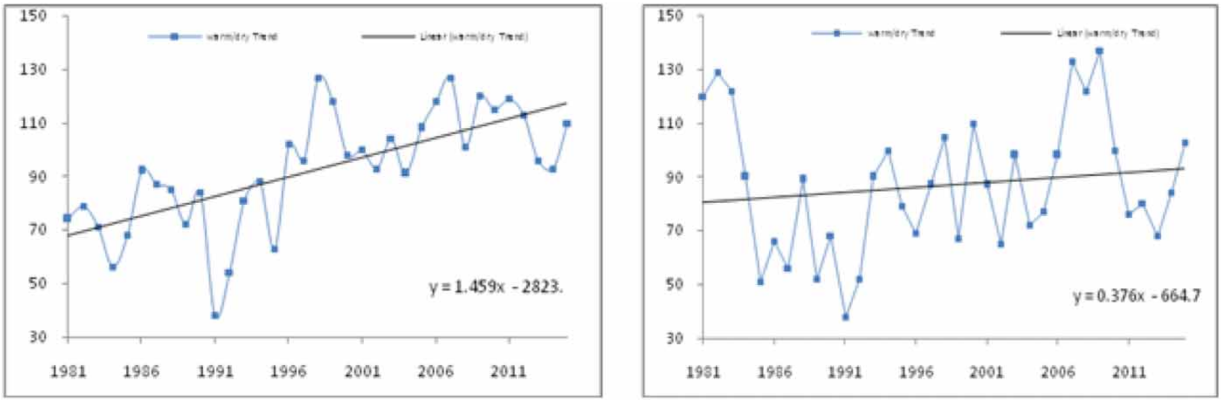

Figure 7 | Time series of the warm/dry (*WD*) extremes for Kish Island (left) and Chabahar (right) stations for the period 1981–2015 (days/decade).

country in the south of the Zagros Mountain range and some dispersed stations, other parts of the country showed negative trends for the *CW* index. However, the *MK* test indicated statistically significant trends at 0.05 levels for only the two stations of Ramsar and Sannandaj in this index. In other words, the number of cold/wet days at the eight stations (17%) had an increase over the study period while the other stations (83%) showed a decreasing trend.

The largest negative trends of the *CW* index can be seen in the northern half of the country and the southern part, especially the south-east of the country. The largest negative trends in *CW* have been found in Sanandaj station, showing a decrease of approximately (−) 1.68 days per decade and Hamedan (Airport) station with the magnitude of approximately (−) 1.12 days per decade (Figure 5).

In some stations, there are very weak positive trends and fluctuations such that there is no significance. In other words, there are no significant trends and regular dispersal of *CW* in these areas.

Generally, Iran experienced a negative trend for *CD* and *CW* indices. It is reasonable to assume that *CD* and *CW* extreme indices are related to general circulation patterns over Iran. The results are consistent with the results of the study by Hao *et al.* (2013) for the Middle East region.

Warm/dry days (WD) and warm/wet days (WW)

Based on our results, the index trend of warm/dry extremes has increased all over the country. The results of the *WD* index (80% of the stations) show the increase at more than 80% of stations (Figure 6(left)). Significant positive trends of *WD* for mountainous ranges, dry and semi-dry climatic regions were recognized. In addition, the significant increasing trends in annual *WD* varied between (+) 3.7 days per decade at Chabahar station and (+) 14.5 days per decade at the Kish Island station (Figure 7). In recent years, in many regions such as central Africa, eastern Australia, and some parts of Russia, the *WD* has increased too (Hao *et al.* 2013). Except for Shahrekord station located in the south-west of the country, the other areas of the country experienced a positive trend in *WD*. This may be due to the cooling trends found for the southern half of the Zagros Mountains and Shahrekord station (Parak *et al.* 2015). Similar behavior in fluctuations in observational extreme precipitation and temperature data sets for 1961–2010 can also be seen in Parak *et al.* (2015). To answer this anomaly needs more research and more precise demands. It should be noted that in some regions, such as southern Zagros (west) and eastern Alborz (north-east), positive trends were non-significant for the number of the *WD* index.

Figure 7 depicts the time series of warm/dry (*WD*) for Kish Island and Chabahar stations. The trend line shows an increase in the annual *WD* since 1981 for Kish Island and Chabahar stations. These stations are located in coastal and marine climates and extreme conditions were modified by marine conditions. Although in these regions temperatures have been affected by the general trend of global warming over the country, local trends can be due to urbanization in these areas. This pattern is important in occurrences of weather phenomena like heatwaves and droughts that cause social and environmental damage (Hao *et al.* 2013). In addition, factors such as local and regional air pollution may influence the nature and magnitude of the climatic trends in different ways (De Sario *et al.* 2013).

Positive trends for the *WD* were found across most of the country which is in parallel with *IPCC* findings. Generally, the period from 1983 to 2012 is much warmer than any 30-year period in the last 1,400 years in the northern hemisphere.

The warm/wet (*WW*) combination trends are shown in Figure 6 (left). The results of linear regression indicate that about 42% of the studied stations show a positive trend in extreme warm/wet index during the past 35 years. However, at the 95% confidence level, few of the observed incremental trends are significant and are mostly located in the north and north-west of the country. Based on the above, most positive trends are relatively weak and non-significant; however, the strongest is at Noushahr station (north of the country) with a trend of (+) 0.56 per decade.

The result also indicated no trends of warm/wet in coastal strips of the Persian Gulf and the south-west and some scattered areas in the country. If the country is divided into two parts with an artificial northeast–southwest line, most of the positive trends are seen on the north side of the line (Figure 6 (right)). Generally, the warm/wet (*WW*) index has incremental trends over the high-latitude regions, whereas the warm/dry indicator has increased in most areas. Our result is consistent with the trend observed in different countries and at the global scale (Beniston 2009; Hao *et al.* 2013).

Although there is a similar behavior between *WW* and *WD*, magnitude and spatial coherence of the earlier index is very weak. Our results indicate that the stations located in the Caspian Sea region such as Ramsar, Noushahr, Rasht have experienced warm/wet days in most years of the period, whereas other stations have experienced some years with no warm/wet days. In the stations located in the south of the country, the *WW* index has been zero in most years. In the warm months, especially in summer, the anticyclonic circulation is strengthened in the west of the Arabian Peninsula, and its extension over this area blocks moisture advection into the south of Iran from the moisture source (Parak *et al.* 2015). This anticyclonic circulation prevents the air from rising and causing precipitation in the area. Such patterns may lead to differences in local climate that may be affected by global warming which tends to make wet areas wetter and dry areas drier (Romm 2015). But the effects differ in different parts of the country. The comparison of results for the indices of *WD* and *WW* days showed a similar behavior between the two indices, but the magnitude and spatial consistency of *WW* days were much less than *WD* days.

UTCI

The results of this study indicate that most of the country generally experienced a reduction in the number of days with cold stress. On the other hand, the increase in terms of warm stress also affects climate comfort conditions in the country. In other words, decreasing trends were found in the annual occurrence of the no thermal stress class, at 45 stations (95%), which was statistically significant ($p < 0.05$) (Figure 8(left)). Negative significant trend rates in *UTCI* in the whole of the country lay in the range of (−) 4 days per decade (Ahvaz station) to −20 days per decade at (Gorgan station).

In a region like the Zagros Mountain range, the negative trends obtained are not so strong. From the results, it is clear that the decreasing trends of the no thermal stress class in the north, northwest, and southeast regions of Iran were stronger than those in the other areas during the last decades.

Our results revealed that positive trends of *UTCI* were only experienced at Ardebil and Shiraz stations in the range of 9–26 °C. The significant positive trend for this index was found in the western regions of the Caspian Sea at Ardebil station by (+) 6.9 days per decade (Figure 9).

Based on the results presented in Figure 8 (left), annual occurrence of strong heat stress (32–38 °C) increased approximately all over the country. Furthermore, the value of the significant increasing trend in this index varied from (+) 0.5 to (+) 17.3 days per decade at Zanjan and Chabahar stations, respectively. Less than one-fifth of the country, including regions in the south and southwest, experienced negative trends or no trends in this index, but stations such as Ahvaz, Abadan, Boushehr, Fasa, Kish Island, Bandar e-lengeh, and Bandarabas showed an increasing trend in *UTCI* events in the annual occurrence of the very strong heat stress (38–46 °C) class.

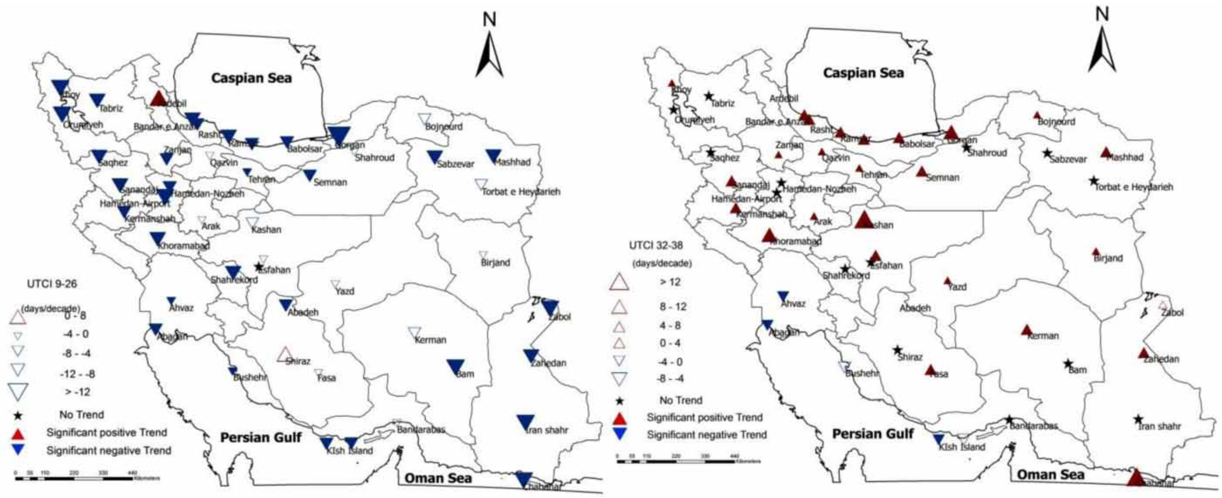

Figure 8 | Decadal trends in occurrences of the *UTCI* in the range of 9–26 °C (left) and in the range of 32–38 °C (right) for the period 1981–2015 (days/decade).

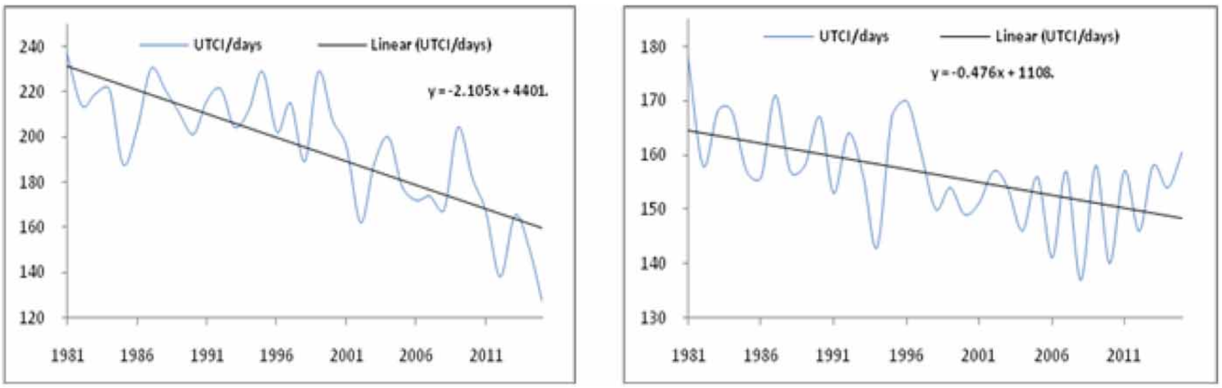

Figure 9 | Time series of the events in the range of 9–26 °C extremes for Gorgan (left) and Ahvaz (right) stations for the period 1981–2015 (days/decade).

Generally, compared with other compound quantities of temperature and precipitation index, *UTCI* is consistent with warming and increases of the warm modes' frequency and the probability of the intensity of the thermal stress is not diminished and has shifted to moderate and high levels. Global warming raises the average temperature which causes heat waves to become more intense and more frequent. For the same reason, heat waves will last longer and cover a large region. In recent years, the severity and frequency of drought has increased due to global warming in many parts of the world (Romm 2015). The results show factors such as topography and latitude play an important role in *UTCI* distribution. In other words, the annual *UTCI* increases with decreasing latitude throughout most of Iran.

TCI

Trends in *TCI*, including the number of days with $TCI \geq 60$, and the number of days with $TCI \geq 80$ are shown in Figure 10. The results indicated that the majority of the trends in the annual *TCI60* and *TCI80* series were positive. The majority of the country showed a positive significant trend in *TCI60*. Significant positive trend rates in the *TCI60* series were in the range of (+) 1.6 days per decade at Rasht station to (+) 16 days per decade at Ardebil station.

The greatest values of this index can be observed in the provinces located in the northwest of the country.

On the contrary, the magnitude of significant negative trends at Chabahar and Gorgan stations located in the

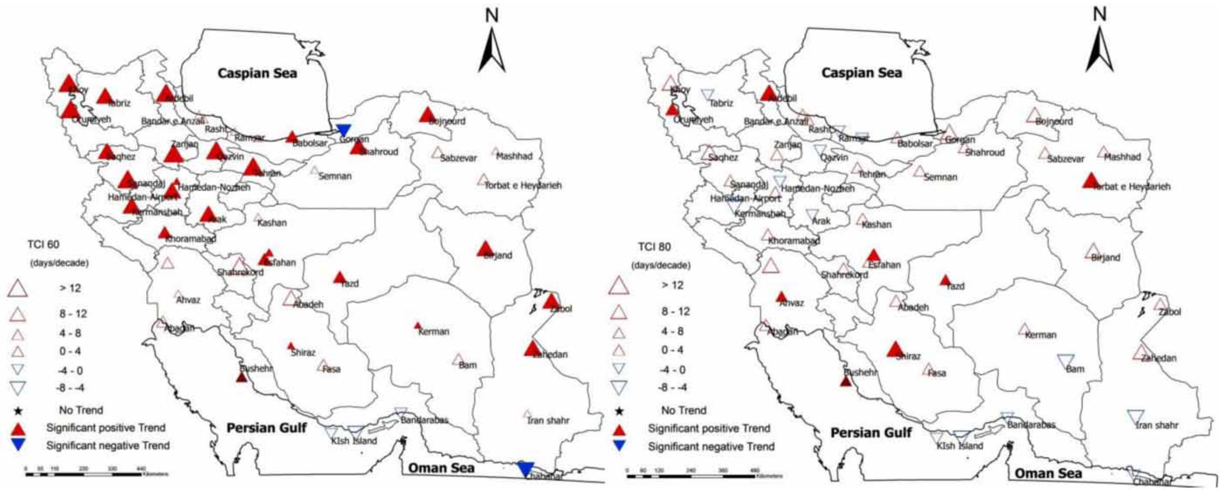

Figure 10 | Decadal trends in the occurrences of the number of days with $TCI \geq 60$ (left) and the number of days with $TCI \geq 80$ (right) for the period 1981–2015 (days/decade).

southeast and north of the country, respectively, showed a significant negative trend. The steepest negative trend was seen at Chabahar station (southeast), showing a decrease of (–) 8 days per decade.

Comparison between $TCI \geq 80$ and $TC \geq I60$ indicated that the $TCI \geq 80$ index has a more irregular distribution than positive and negative trends in the country. Over 75% of the stations studied in the country showed an increase in the annual occurrence of $TCI \geq 80$ and 17% of these have significant increasing trends (Figure 10(right)). The largest positive significant trend in $TCI \geq 80$ was found at Ardebil station, which shows an increase of 10 days per decade.

About 20% of the stations, mostly in the northwest and southeast of the country, had negative trends. The largest negative trend occurred at Iranshahr station, showing a decrease of (–) 2.2 days per decade. Generally, the relationships that have been observed may be explained by several physically different mechanisms. Such correlations may occur because of changes in cloud cover or changes in precipitation and the consequent changes in the heat balance of the regions under consideration (Zhao & Khalil 1993). Thus, it is worth mentioning the issue of whether the observed trends were related to a long-term process like global warming or if they were part of a multi-decadal natural oscillation. Further studies would be interesting to compare the trends found in our study with the results of other tests to detect trends.

CONCLUSION

This paper has attempted to provide an appropriate consideration of extreme climate process by using compound extreme index with a primary focus on extreme events. There were long-term records for a few stations before 1981. There are some limitations for most stations, such as inhomogeneities and uncertainties in their data sets caused by changes like location, exposure, instrumentation, and observation practice, and also from missing data. We used synoptic stations whose data were reliable, continuous, and long. These stations cover most of the climate types and are evenly geographically distributed throughout the country. These indices were calculated and analyzed for 47 sites during 1981–2015 to provide a general overview of climate change in Iran. Climatic variables such as temperature, precipitation, humidity, sunshine, and wind speed were analyzed. The results of non-parametric tests highlighted the statistically significant spatially coherent trends in compound values of temperature and precipitation index (using the 25% and 75% value levels) corresponding to a warming trend in the country. It was concluded that in more than 80% of Iran the frequency of the warm modes has increased while the frequency of cold modes has decreased but with smaller magnitudes. Generally, Iran experienced a negative trend for the CD and CW index and a positive trend in CW was observed in some dispersed small areas.

More than 97% of the stations exhibited a positive trend for the annual *WD* index. Positive trends for the *WD* were found all over the country which is in parallel with *IPCC* findings. The results of linear regression indicate that about 42% of the studied stations show a positive trend in extreme warm/wet index that are seen in the northern half of the country. The rate of the significant increasing trends in annual *WD* varied from (+) 3.7 days per decade at Chabahar station to (+) 14.5 days per decade at Kish Island station. Based on the results of the analysis, apart from a few stations and, more specifically, in Shahrekord station, the overall patterns of compound values of temperature and precipitation show the same trend, and responding to these differences definitely requires further investigation. Both *WD* and *WW* indices have similar behavior, but the magnitude and spatial consistency of *WW* days were much less than *WD* days. The results show that most of the country generally experienced a reduction in the number of days with cold stress and an increase in warm stress. These factors affect climate comfort conditions in the country.

Based on the results, *UTCI* is consistent with warming and increases of the warm mode frequency and the probability of the intensity of the thermal stress is not diminished and has shifted to moderate and high levels. Global warming raises the average temperature that causes heatwaves to become more intense and more frequent. At the same time, the occurrence of *TCI* and *UTCI* in strong heat stress (32–38 °C) events has increased over most of the country, consistent with increases in the warm modes' frequency. The majority of the country showed a positive significant trend in $TCI \geq 60$, and $TCI \geq 80$ index has a more irregular distribution than positive and negative trends in the country. The distribution of the annual compound index trends indicated that the negative and positive significant trends mainly occurred in the northwest of Iran. The results also suggest the need for further investigation on the intervention of local factors in the environment, which could be one of the major causes of climate change. The findings of this study confirmed the results of previous studies (e.g., *IPCC* 2007). Although our results are consistent with the findings of other studies such as a Middle East regional study (Zhang *et al.* 2005, 2011) and trends of climate extremes over Iran (Parak *et al.* 2015), the results also suggest the need for further investigation by using gridded daily data and remote sensing data on local anthropogenic factors, which could be one of the major causes of climate change in Iran.

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