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Investigating the Trend Changes in Temperature Extreme Indices in Iran

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Abstract: It is necessary to evaluate the response of extreme events to global warming across different climates and geographical regions. This study aims to examine the trend changes of 13 temperature extreme indices over a 30-year statistical period from 1990 to 2020, using daily maximum and minimum temperature data from 37 synoptic stations in Iran. The Mann–Kendall trend test was employed to analyze the data trends. The results indicate that, except for the two indices, frost days (FDs) and ice days (IDs), the temperature extreme indices show an increasing trend across the country. The forward and backward graphs of the Mann–Kendall test reveal that the trend of the indices is significant at the 0.05 significance level, with the two indices TNn and TXn intersecting in 2009. This indicates that a mutation occurred in that year, where the increasing slope of the trend after the mutation is greater than the slope of the trend before the mutation. Moreover, the decadal changes of the indices in the three decades 1990–2000, 2000–2010, and 2010–2020 demonstrate that the highest increasing trend in temperature occurred in the second and third decades.

Keywords: Iran; Mann–Kendall test; climate change; temperature extreme indices

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1. Introduction

After the Industrial Revolution, human activities increased rapidly, resulting in a higher concentration of greenhouse gases in the atmosphere. This surge has adversely affected the climate [1,2]. According to the sixth report of the Intergovernmental Panel on Climate Change (IPCC), the world's temperature has increased by 0.99 degrees Celsius from 2001 to 2020, compared to the period from 1900 to 1950 [3]. Additionally, extreme climate events, such as severe droughts, heat waves, and changes in precipitation patterns, are among the negative impacts of climate change [4,5].

Different countries are attempting to quantify the effects of climate change to mitigate its destructive impacts. In recent decades, there has been a significant focus on studying changes in climate parameters. In [6], the authors noted that temperature, environment, precipitation, greenhouse gases, risk, and biodiversity are essential fields of research related to climate change in the early years of the 21st century. Therefore, it is crucial to investigate changes in climate extreme indices over an extended period. Examining trends in extreme events enhances the reliability of climate models and predictions. Consequently, at the end of the 1990s, the specialized team for the monitoring and detection of climate change indices (ETCCDMIs), in cooperation with the Climatology Commission (CCI), the World Meteorological Organization, and the Climate Variability and Prediction Project (CLIVAR), developed 27 climate extreme indices related to precipitation and temperature [7]. Based

on ref. [8] on climate extremes, this study analyzed quality-controlled daily temperature and precipitation data from 1961 to 2015 to assess changes in climate extreme indices across Tanzania. Utilizing tools such as RClimdex and the National Climate Monitoring Products (NCMP) developed by the WMO Commission for Climatology, the study identified a statistically significant increase in temperature extremes, including a increase in the frequency of warm days and warm nights, along with a decrease in cold days and nights.

In a study, ref. [9] calculated the trends of 16 temperature extreme indices using daily maximum and minimum temperature data, the non-parametric Mann–Kendall test, and Sen's slope in the RClimdex 1.0 software environment. Their results showed a significant positive trend in the time series of temperature indices. They also reported that daily warming occurs in some areas while warmer nights are observed in others.

In another study, ref. [10] analyzed climate extreme indices in Cherrapunji (1979–2020) using the Mann–Kendall test. They found an increase of 0.06–0.07 °C per year in maximum daily temperature indices, with notable trends in February and November for minimum temperature indices. They warned about potential climate change threats.

In [11], the authors conducted a study in Xinjiang, China, using daily temperature and precipitation data to analyze extreme indices from 1960 to 2019 with Sen's slope and the Mann–Kendall test. Results showed a downward trend in frost days (FDs), ice days (IDs), cold days (TX10p), cold nights (TN10p), and the cold spell duration index (CSDI). In contrast, summer days (SD25), warm days (TX90p), warm nights (TN90p), and the warm spell duration index (WSDI) exhibited upward trends. All extreme temperature events correlated strongly ($R > 0.6$) with the average annual temperature. In [12], the authors analyzed the mean temperature and variations of 10 temperature extreme indices recommended by ETCCDI at 25 stations in Nepal from 1986 to 2015. Their findings indicated that maximum temperature increased faster (0.40 °C per year) than minimum temperature (0.20 °C per year), differing from trends in the Tibetan Plateau. The study highlighted spatiotemporal heterogeneity in global average temperature extremes. Additionally, there was an annual increase in cold events and a decrease in days below the tenth percentile, along with a negative trend in the TNn and TXn indices. In a study by [13], nine climate extreme indices defined by ETCCDI were assessed using long-term data from 70 meteorological stations in Northeast China (1960–2014). Sen's slope estimator and R/S analysis were used to identify spatial and temporal changes, while the Morlet continuous wavelet transform calculated extreme index intervals. The results showed significant decreasing trends in frost days (FDs) and ice days (IDs), while summer days (SU25), tropical nights (TR20), and warm days (TX90) exhibited significant increases. In [14], the authors investigated trends in daily temperature extreme indices across Ethiopia using 14 indices and the Mann–Kendall trend test. Analyzing data from 34 stations in three zones, the results showed that annual maximum temperatures increased by 2.68 °C per decade, minimum temperatures by 2.04 °C per decade, and the diurnal temperature range (DTR) by 0.62 °C per decade. About 73.5% of stations showed an increasing trend for extreme maximum temperature (TXx), while 26.5% did for extreme minimum temperature (TNx). Extreme warm and cold temperature indices exhibited contrasting variations, with most increasing trends found in Northern and Southeastern Ethiopia.

In a study, ref. [15] evaluated changes in spatiotemporal patterns of extreme climate indices using daily maximum and minimum temperature data and precipitation from 50 Iranian meteorological stations (1975–2010). Sixteen indices were analyzed, including five temperature indices and 11 precipitation indices. Results indicated an increase in extreme temperature events, with most stations showing statistically significant trends for temperature indices. However, no systematic regional trends were observed for total precipitation or extreme precipitation indices during this period. In another study, ref. [16]

examined temperature extreme indices from 33 synoptic stations in Iran (1960–2014) and analyzed their relationship with altitude and latitude. The findings revealed a significant warming trend, especially in daily minimum temperature indices. At lower altitudes, the indices reflected a warming climate, while at higher altitudes, they exhibited mixed trends. No significant relationship was found between the trends of the indices and latitude. Additionally, ref. [17] investigated temperature changes and extreme precipitation indices using daily data from 76 synoptic stations in Iran from 1981 to 2010. They applied the Mann–Kendall trend test and Sen's slope estimator. The results indicated that warm temperature indices generally increased, while cold indices decreased. For extreme precipitation indices, there was a decreasing trend in both the amount and intensity of precipitation, along with an increase in the number of consecutive dry days. In [18], the authors examined daily temperatures from 27 synoptic stations in Iran to analyze changes in temperature extreme indices across five categories: percentiles, absolute, extreme, periodic, and others, from 1951 to 2003. Their results indicated that indices such as frost days (FDs), ice days (IDs), cold days (TX10P), cold nights (TN10P), and the diurnal temperature range (DTR) show a negative trend in most regions of Iran. In contrast, indices such as summer days (SU25), warm days (TX90P), and warm nights (TX90P) are increasing in most areas of the country. In [19], the authors investigated 16 temperature extreme indices in the Khorasan region using 25 years of daily temperature data from 14 synoptic stations, covering the period from 1987 to 2011. Their findings showed that over 90% of the stations exhibited temperature changes consistent with warming trends. It can be concluded that Greater Khorasan has experienced significant temperature changes, particularly warming, over the past 25 years. Based on the observed indicators, the intensity of these changes is expected to increase in the coming decades.

By examining the history of studies on extreme events, especially temperature events, it is clear that temperature events have an increasing trend, such that the number of cold days and nights is decreasing while the number of warm days and nights is increasing. Extreme climate events have become a primary global concern. It is essential to evaluate these events across different climates and geographical regions worldwide, especially in developing countries such as Iran, which cannot adapt to these changes and are significantly affected by such climatic extremes, to understand the uncertainties in response to extreme climatic events to global warming, Additionally, the trend of temperature increase from 2001 to 2020 is higher than in previous periods, leading to more frequent extreme temperature events worldwide. Therefore, assessing the changing trends of extreme events in various regions is necessary to understand how these temperature extremes are evolving. This understanding may have profound implications for various sectors, including irrigation water use, physiological stress in crops, respiratory and heart diseases, reproductive cycles, and insect populations. It will also provide decision-makers with the information needed to develop new technologies and systems to mitigate the adverse effects of climate change and adapt to this phenomenon. Due to the fact that Iran is considered one of the arid and semi-arid regions of the world with diverse climates, it is particularly vulnerable to the negative impacts of climate change. Furthermore, the trend of temperature increase from 2001 to 2020 has surpassed that of previous periods, and since earlier studies primarily focused on data up to the 2000s, there is a pressing need for continuous monitoring of extreme events. This study aims to investigate the changes in the trends of 13 temperature extreme indices, analyze the correlations among these indices, and examine the decadal changes of these indices in Iran over a 30-year period from 1990 to 2020 at 37 synoptic stations. Furthermore, another aim of this study is the identification of mutation points in the time series of temperature extreme indices, which serve as starting points for climate events. This aspect has been examined in very few studies across Iran. The remainder of

this study is organized as follows: Section 2 describes the study area, the meteorological stations used, and the data analysis method. Section 3 presents the results and discussion. Finally, Section 4 concludes this study and offers suggestions for future research.

2. Materials and Methods

2.1. Study Area and Quality Check of Data

Iran is a high plateau covering an area of 1,648,195 km^2, located between 25° and 40° N latitude and 44° and 64° E longitude in Southwest Asia (Figure 1). This country borders the Caspian Sea to the north and the Oman Sea and the Persian Gulf to the south. Iran exhibits significant climate diversity from north to south, due to its wide range of latitudes and longitudes; the cities along the northern coast experience a humid climate. At the same time, the southern coastal areas have a dry climate, marked by a significant shortage of water resources, frequent droughts, and a high dependence on groundwater [20]. In most regions of the country, annual precipitation ranges from less than 50 mm to about 350 mm [21].

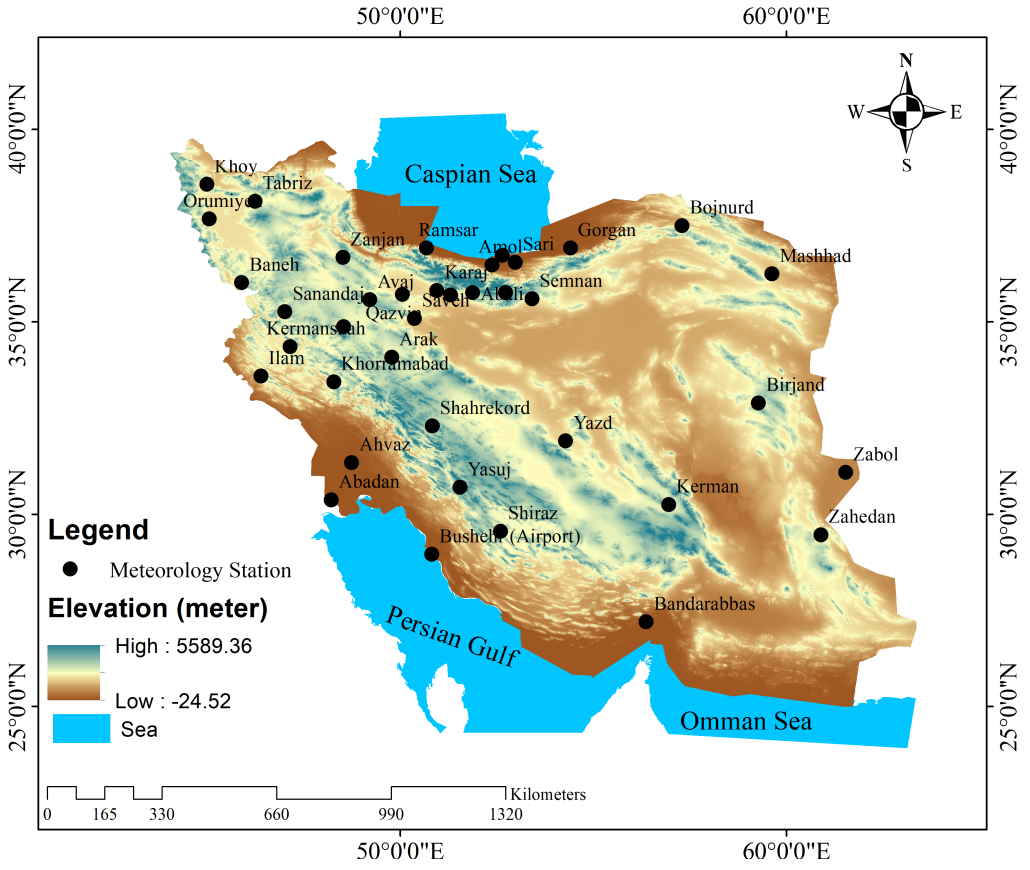


Figure 1. Location of Iran and meteorological stations used in this study with Digital Elevation Model (DEM).

In this study, we selected several national synoptic stations with long-term daily maximum and minimum temperature data. After ensuring data quality, we selected 37 stations with reliable long-term data from 1990 to 2020 provided by the Islamic Republic of Iran Meteorological Organization (IRIMO). The locations of these meteorological stations are depicted in Figure 1. Homogeneity testing is crucial in climatological research, especially when evaluating climate change [22]. Climate data recorded by weather stations over a long period are inevitably influenced by non-climatic factors such as changes in instruments, observers, site locations, or surrounding environments [23]. In this study, we used the

RHtests V4_dlyPrcp software in the R programming language to assess the homogeneity of precipitation data. This software can identify and adjust for artificial shifts in climate data series unrelated to climate change (https://github.com/ECCC-CDAS/RHtests, accessed on 1 March 2019). The results of RH tests indicated that there were no significant inhomogeneities that required mean adjustments. Subsequently, we calculated 13 temperature extreme indices defined by ETCCDI (Table 1) based on the daily maximum and minimum temperature data.

Table 1. Information for temperature extreme indices defined by ETCCDI used in this study.

Index	Index Name	Index Definition	Unit
TXx	Hottest day	Maximum of daily maximum temperature in period.	°C
TNx	Warmest night	Maximum of daily minimum temperature in the period.	°C
TXn	Coldest day	Minimum of daily maximum temperature in period.	°C
TNn	Coldest night	Minimum of daily minimum temperature in the period.	°C
FD	Frost days	Annual count of days when daily minimum temperature < 0 °C.	day
ID	Ice days	Annual count of days when daily maximum temperature < 0 °C.	day
DTR	Diurnal temperature range	Annual mean of the daily difference between minimum and maximum temperature.	°C
SU25	Summer days	Annual count of days when daily maximum temperature > 25 °C.	day
TR20	Tropical nights	Annual count of days when daily minimum temperature > 20 °C.	day
TX10p	Cold days	Percentage of time when daily max temperature <10th percentile.	%
TN10p	Cold nights	Percentage of time when daily max temperature <10th percentile.	%
TN90p	Warm nights	Percentage of time when daily min temperature >90th percentile.	%
TX90p	Warm days	Percentage of time when daily max temperature >90th percentile.	%

2.2. Data Processing Method

2.2.1. Mann–Kendall (MK) Trend Test

In this study, we used the Mann–Kendall trend test [24,25], also known as the MK test, to identify any significant trends in the selected time series of climate variables. The MK test is a nonparametric test that does not rely on the linearity or normal distribution of the time series data. Furthermore, the MK test can identify monotonic upward or downward trends in a time series. Ref. [26] defined the MK statistic (S) as follows:

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

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} +1 \text{ if} (x_j - x_i) > 0 \\ 0 \text{ if} (x_j - x_i) = 0 \\ -1 \text{ if} (x_j - x_i) < 0 \end{cases} \tag{2}$$

where x_j and x_i are the jth and ith terms, respectively, in the time series of size n. Equation (2) calculates the number of positive differences minus the number of negative differences. Thus, a positive S suggests that the most recent data are larger than the previous data, thus having an upward trend, while a negative S suggests the contrary. For $n \geq 10$, the average E and variance (Var) of S are given in Equations (3) and (4).

$$E(S) = 0 \tag{3}$$

where the mean is 0 since the authors of [27] already proved that S is asymptomatic and normally distributed for time series with $n \geq 10$.

$$\operatorname{Var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{i=1}^{1} t_i(t_i-1)(2t_i+5)\right] \tag{4}$$

where t is the number of tied groups in the time series, and t_i is the volume of data in the ith tied group. The statistics of the standard test (Z) can be calculated as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} \text{ if } S > 0 \\ 0 \text{ if } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} \text{ if } S < 0 \end{cases} \quad (5)$$

where Z is used to evaluate the significance of the trend by testing the null hypothesis (H0). For the Mann–Kendall trend test, H0 assumes that there is no monotonic trend in the data, and the alternative hypothesis (Ha) implies that a trend exists in the time series.

If $|Z| > Z_{1-\frac{\alpha}{2}}$, H0 is rejected, and Ha is accepted, thus implying that the trend is significant at the chosen significance level (a). Based on the two-tailed test, the values of Z for significance levels 5% and 10% are ± 1.96 and ± 1.64, respectively. For example, if the value of Z falls in the range of ± 1.96, H0 is accepted, thus implying that the trend is non-significant. However, if $|Z| > 1.96$, then H0 is rejected, thus implying that the trend is significant at $\alpha = 0.05$. A positive sign of Z indicates an upward trend, and a negative sign indicates a downward trend.

2.2.2. Detection of Mann–Kendall Mutation

The MK test is used to determine whether a series is increasing or decreasing over time. This test provides graphical results and can also identify the starting point of the trend [27]. Time series (D_2, D_3, . . . , and D_n) constructs an orderly column r_i, which represents the sample accumulation number of $D_i > D_j (1 \leq j \leq i)$. The rank series ($S_k$) is calculated as follows:

$$S_k = \sum_{i=1}^{k} r_i (k = 2,3, \ldots, n) \quad (6)$$

When $D_i > D_j$, $r_i = 1$; when $D_i _ D_j$, ri = 0 (j = 1, 2, . . ., i). The expected value $E(S_k)$ of S_k and its sequence variance Var (S_k) are calculated as follows:

$$E(S_k) = n(n+1)/4 \quad (7)$$

$$Var(S_k) = n(n-1)(2n+5)/72 \quad (8)$$

The data sequence is considered independent, and the test statistics (UF_k) is calculated as follows:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{Var(S_k)}} (k = 1,2, \ldots, n) \quad (9)$$

UFk follows a standard normal distribution and represents a significance level, denoted by a. The critical value Uα can be obtained from the standard normal distribution table. For instance, if a is set to 0.05, we can determine the corresponding critical value U. ± 1.96. If $|UF_k| > |U\alpha|$, it indicates a significant increase or decrease trend in the time series. We plotted the UF_k points for the study period as a curve to analyze whether there was a decreasing or increasing trend. Then, we repeated the steps in reverse order. We multiplied the resulting value by -1 to obtain a new time series, called UB_k. We drew sequence diagrams for both (UF_k or forward) and (UB_k or reverse). If $UF_k > 0$ or $UF_k < 0$, it means there is an increasing or decreasing trend, respectively. When UF_k exceeds the critical value, the increasing or decreasing trend becomes statistically significant. The intersection point between the UF_k and UB_k curves indicates the start of a mutation [28,29].

2.2.3. Pearson Correlation Coefficient (r)

To determine the correlation of temperature extremes indices with each other, Pearson's correlation coefficient was used according to Equation (10):

$$r = S_{xy}/S_xS_y \quad (10)$$

where S_{xy}, S_x, and S_y are the covariance between x and y, the standard deviation of x, and the standard deviation of y, respectively.

The data analyses were conducted using R4.3.2 software, and the maps were created using ArcGIS 10.7.1 (ESRI Inc., Redlands, CA, USA) and SPSS Statistics version 26.

3. Results and Discussion

3.1. Analysis of Trend Change and Mutation Point

Figure 2 shows the linear trend of temperature extreme indices in Iran. The extreme indices TX90, TN90, TR20, TX10, TN10, DTR, TXx, TNx, TXn, and SU25 exhibit an increasing trend throughout the statistical period, with a more pronounced rise in the third decade (2010–2020). For the indices TNn and TXn, although there was a decline in their time series in 2008, they show an upward trend after that year, continuing until the end of the period. In contrast, the FD and ID indices demonstrate a decreasing trend throughout the period, with a more significant decline observed toward the end. Additionally, the Mann–Kendall test statistic was employed to identify mutations and assess the trends of increase or decrease in temperature extreme indices (Figure 3). According to these charts, of the 13 temperature extreme indices, two indices, ID and FD, show a decreasing trend during the study period. Between 1998 and 2005, the leading chart of the indices falls outside the significance level, indicating a significant decrease in both the number of frost days and the number of ice days during this time. The trends for the TX90, TN90, TR20, TX10, TN10, DTR, TXx, TNx, and SU25 indices during the study period are increasing, such that by the end of the period, the leading and regressive graphs fall outside the significance level at the 0.05 level, signifying that the increasing trend of these indices is significant.

Additionally, Figures 1 and 2 indicate that most indices experienced changes in their trends from 2000 to 2010, with the increasing or decreasing slopes becoming more pronounced compared to the preceding period. The two extreme indices, TNn and TXn, showed an increasing trend until 2008. In that year, the leading and regressive graphs for these indices intersected, signaling a mutation in the data series, although this jump is not significant. Following this intersection, the indices increased at a steeper slope than they had before the mutation. Overall, as we approach the end of the statistical period, the rate of increase becomes more pronounced.

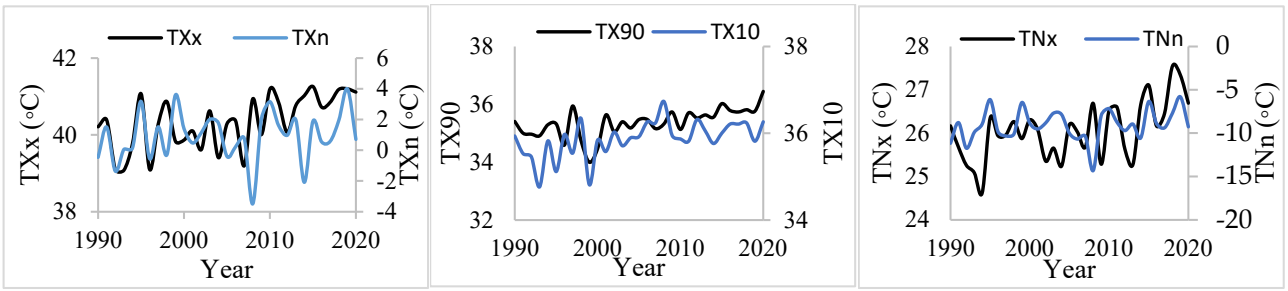


Figure 2. *Cont.*

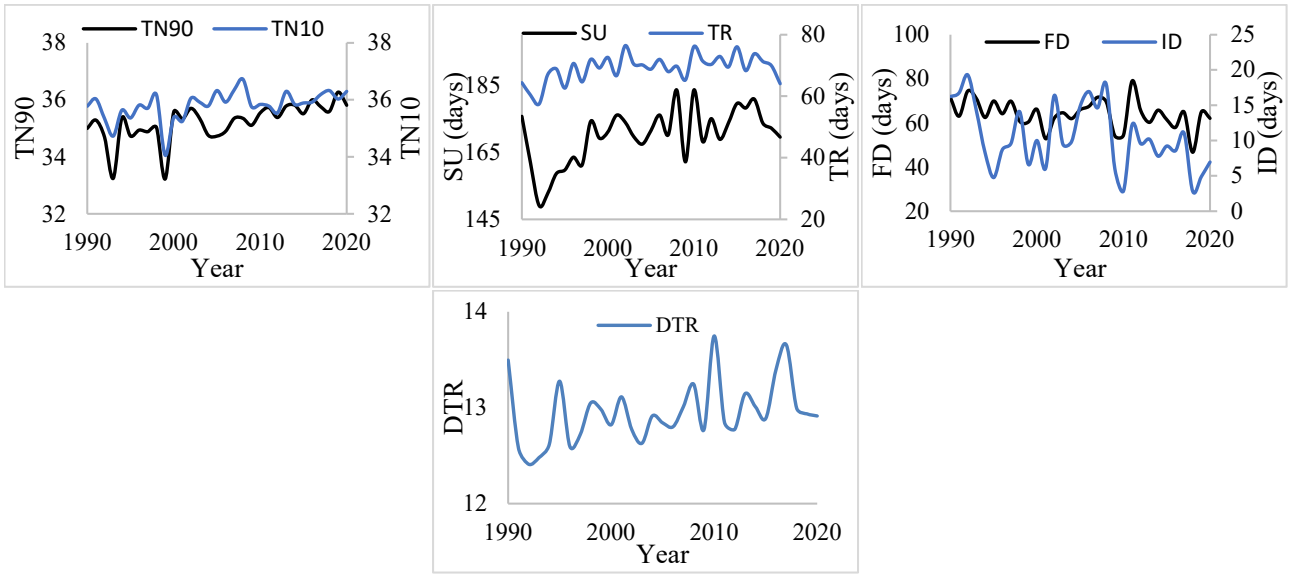


Figure 2. Linear trends of temperature extreme indices: TXx, TXn, TX90, TX10, TNx, TNn, TN90, TN10, SU, TR, FD, ID, DTR.

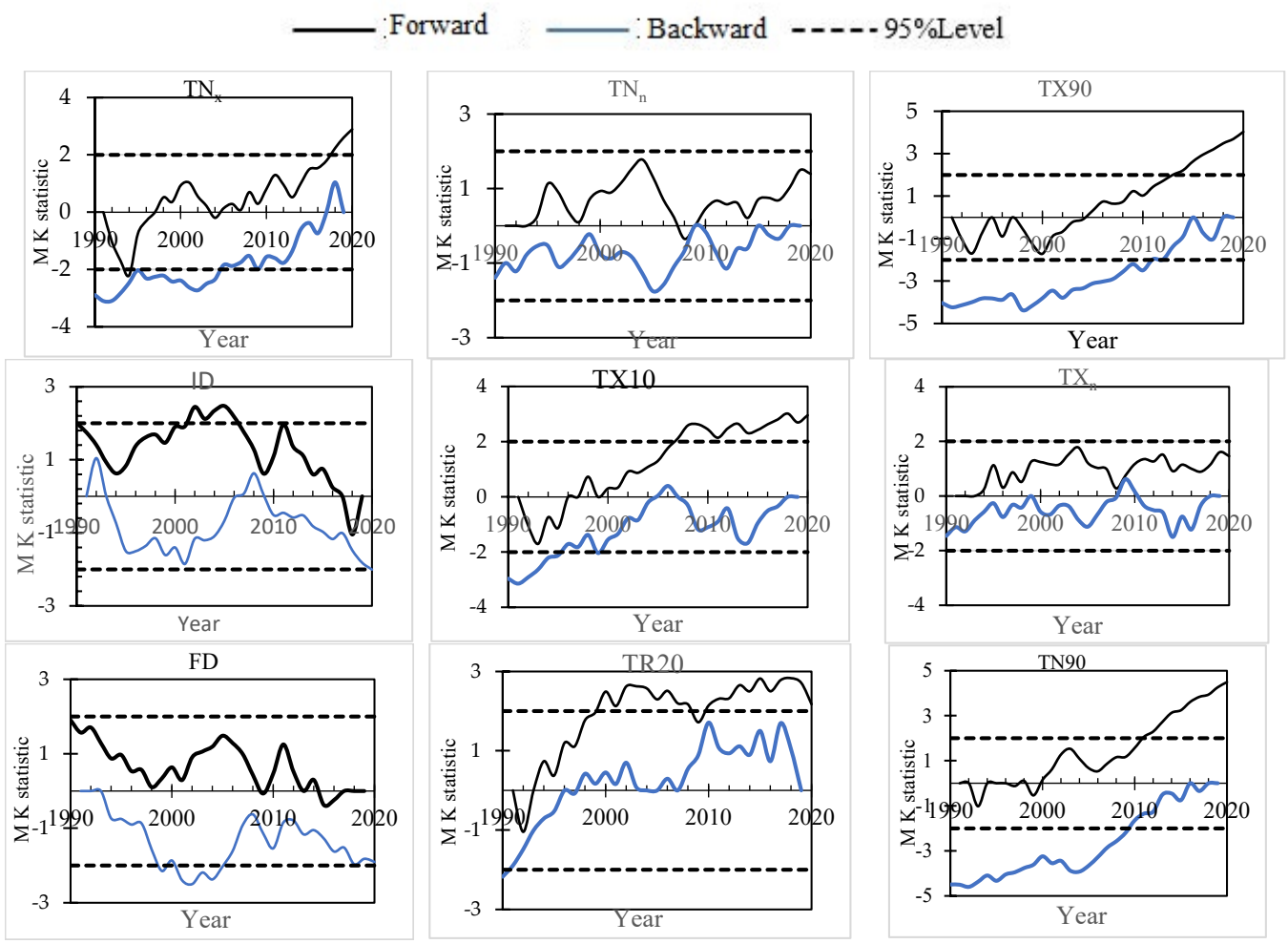


Figure 3. *Cont.*

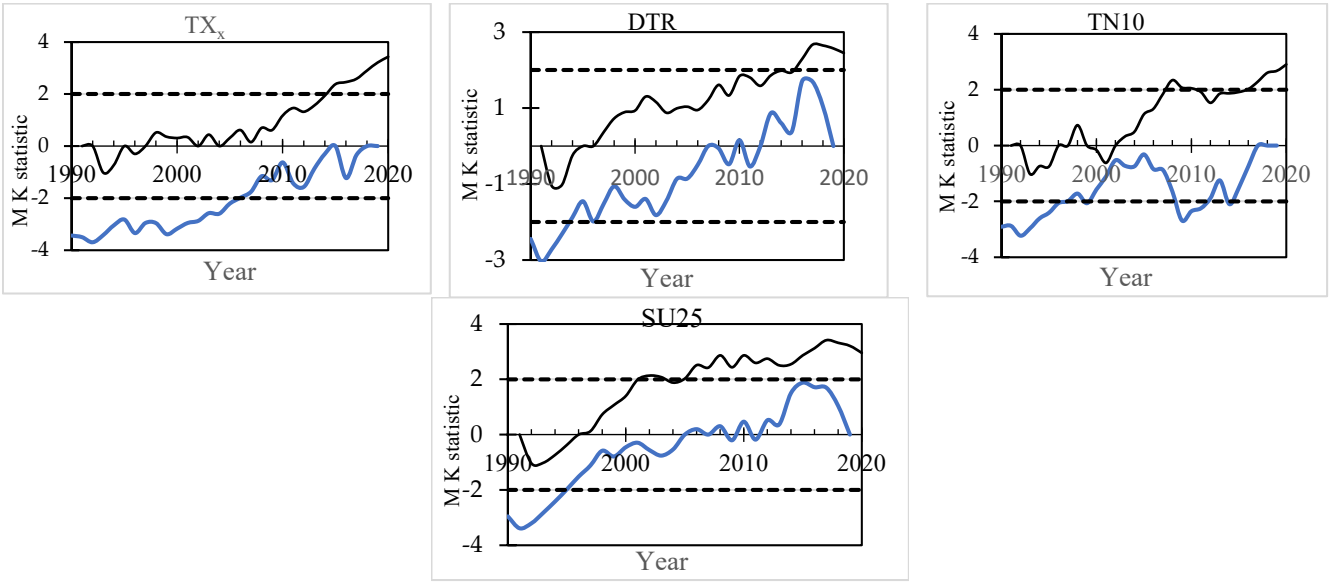


Figure 3. Mann–Kendall statistics of maximum and minimum temperature extreme indices. Progressive and retrograde are forward and reverse data sequence Mann–Kendall statistics.

3.2. Correlation Coefficients of Temperature Indices

The Pearson correlation coefficient values between the temperature extreme indices were calculated for the study area (Table 2). The aim of this section is to calculate the correlation between temperature extreme indices and to analyze the relationship between cold and warm temperature indices. According to this table, there are significant correlations among the indices. Warm indices exhibit a positive and significant correlation with each other (SU25, TR, TXx, TNx, TX90, TN90), while cold indices (FD, ID, TNn, TXn, TX10, TN10) also show positive and significant correlations among themselves. Additionally, the correlation between warm and cold indices reveals a negative relationship. The correlation table indicates that the highest positive and significant correlations are between the indices TNn and TXn (0.928 **), TN90 and TX90 (0.734 **), TNx and TR (0.903 **), TR and TXn (0.878 **), and SU25 and TXx (0.899 **). Conversely, the highest negative significant correlations occur between the indices FD and TNn (−0.953 **), TNn and ID (−0.687 **), and TNx and ID (−0.650 **). Overall, the negative correlation between cold and warm extreme indices indicates that the trends of these indices in Iran during this time period are reversed: warm extreme indices have shown an increasing trend, while cold extreme indices have displayed a decreasing trend. The findings of this study are consistent with those of [14], who reported that cold, extreme temperature extreme indices exhibit opposite changes to warm extreme indices.

Table 2. The Pearson correlation coefficient matrix of temperature extreme indices in Iran.

	DTR	FD	TN10P	TN90P	TNN	TN$_X$	TR	ID	SU	TX10	TX90	TX$_N$	TX$_X$
DTR	1												
FD	0.366 *	1											
TN10P	0.177	0.381 *	1										
TN90P	−0.288	−0.213	0.313	1									
TNn	−0.407 *	−0.953 **	−0.282	0.259	1								
TN$_X$	−0.152	−0.874 **	−0.386 *	0.047	0.857 **	1							
TR	−0.303	−0.860 **	−0.322	0.087	0.905 **	0.903 **	1						

Table 2. *Cont.*

	DTR	FD	TN10P	TN90P	TNN	TN_X	TR	ID	SU	TX10	TX90	TX_N	TX_X
ID	−0.036	0.783 **	0.235	−0.137	−0.687 **	−0.650 **	−0.555 **	1					
SU	0.235	−0.675 **	−0.154	−0.007	0.698 **	0.806 **	0.759 **	−0.690 **	1				
TX10	0.420 **	0.085	0.425 **	0.167	−0.001	0.051	0.035	−0.076	0.403 *	1			
TX90	−0.622 **	−0.396 *	0.259	0.734 **	0.430 **	0.165	0.304	−0.119	−0.022	−0.098	1		
TX_N	−0.154	−0.855 **	−0.187	0.21	0.928 **	0.812 **	0.878 **	−0.720 **	0.858 **	0.204	0.289	1	
TX_X	0.359*	−0.568 **	−0.216	−0.005	0.549 **	0.779 **	0.650 **	−0.608 **	0.899 **	0.412 *	−0.121	0.670 **	1

** Correlation is significant at the 0.01 level. * Correlation is significant at the 0.05 level.

3.3. Decadal Change of Temperature Extreme Indices

The changes in temperature extreme indices over three decades (1990–2000, 2000–2010, and 2010–2020) were calculated for all studied stations (Table 3). According to this table, the FD, ID, and TNn indices have been decreasing. Specifically, the ID index consistently decreased over each three-decade interval, with a more significant decrease observed between the second and third decades. The FD index experienced a slight decrease between the first and second decades before stabilizing. The TNn index showed a decreasing trend between the first and second decades, followed by an increasing trend afterward, with an increase of 0.9 °C.

Table 3. Decadal changes in temperature extreme indices in the three decades 1990–2000, 2000–2010, and 2010–2020 during the statistical period of 1990–2020.

Index	1990–2000 (Decade 1)	2000–2010 (Decade 2)	2010–2020 (Decade 3)	Decade Changes 1–2	Decade Changes 2–3	Unit
DTR	12.8	13.0	13.1	0.0	0.0	°C
FD	67.0	63.0	63.0	−4.0	0.0	day
ID	12.0	11.0	8.0	−1.0	−3.0	day
SU	163.0	173.0	174.0	10.0	1.0	day
TN10	35.0	36.0	36.0	1.0	0.0	day
TN90	35.0	35.0	36.0	0.0	1.0	day
TNn	−9.3	−9.4	−8.5	−0.1	0.9	°C
TNx	25.8	25.9	26.5	0.1	0.7	°C
TR	66.0	70.0	71.0	4.0	1.0	day
TX10	36.0	36.0	36.0	0.0	0.0	day
TX90	35.0	35.0	36.0	0.0	1.0	day
TXn	0.8	0.8	1.2	0.0	0.4	°C
TXx	40.0	40.2	40.9	0.20	0.7	°C

On the other hand, the DTR and TX10 indices did not show any average changes over the three decades, maintaining a value of zero. The SU25, TN10, TN90, TNx, TR, TX90, TXn, and TXx indices increased over the three decades, with the most significant change observed in the SU25 index between the first and second decades. Additionally, the TR index increased by four days between the first and second decades. Overall, the results indicate that temperature extreme indices in Iran are increasing, with the most significant changes occurring in the second and third decades, except for the SU index, which experienced the most significant increase in the first and second decades. The two

extreme indices, ID and FD, exhibit a downward trend in Iran, with the ID index showing a more significant decrease. The results of this research are consistent with the findings of other researchers, including [14,15].

3.4. Analysis of Spatial Variation in the Trend of Temperature Extremes Indices

Figure 4 shows the trend of temperature extreme indices at study stations in Iran from 1990 to 2020. During this period, the DTR index increased in most stations across the country, with only a limited number of stations showing a different trend. The FD index decreased in most regions, except for a few stations in the southwestern parts of the country, where its trend was increasing. The ID index, similar to the FD index, decreased in almost all regions, except a few stations in the northern part of the country, such as Gorgan, Sari, Firouzkoh, and the Zabul and Zahedan stations in the southeast. The SU25 index exhibited a significant increasing trend at the 0.05 level across all study stations, indicating an upward trend in summer days during this period. The TN10 index also shows an increasing trend at most stations, except for a few in the north and southwest that exhibit a decreasing trend. The TN90 index has an increasing trend at most study stations, with some exceptions primarily located in the west and northwest of the country. Additionally, there was a significant increase in seven situations—Birjand, Kerman, Arak, Qazvin, Zanjan, Khorramabad, and Hamadan.

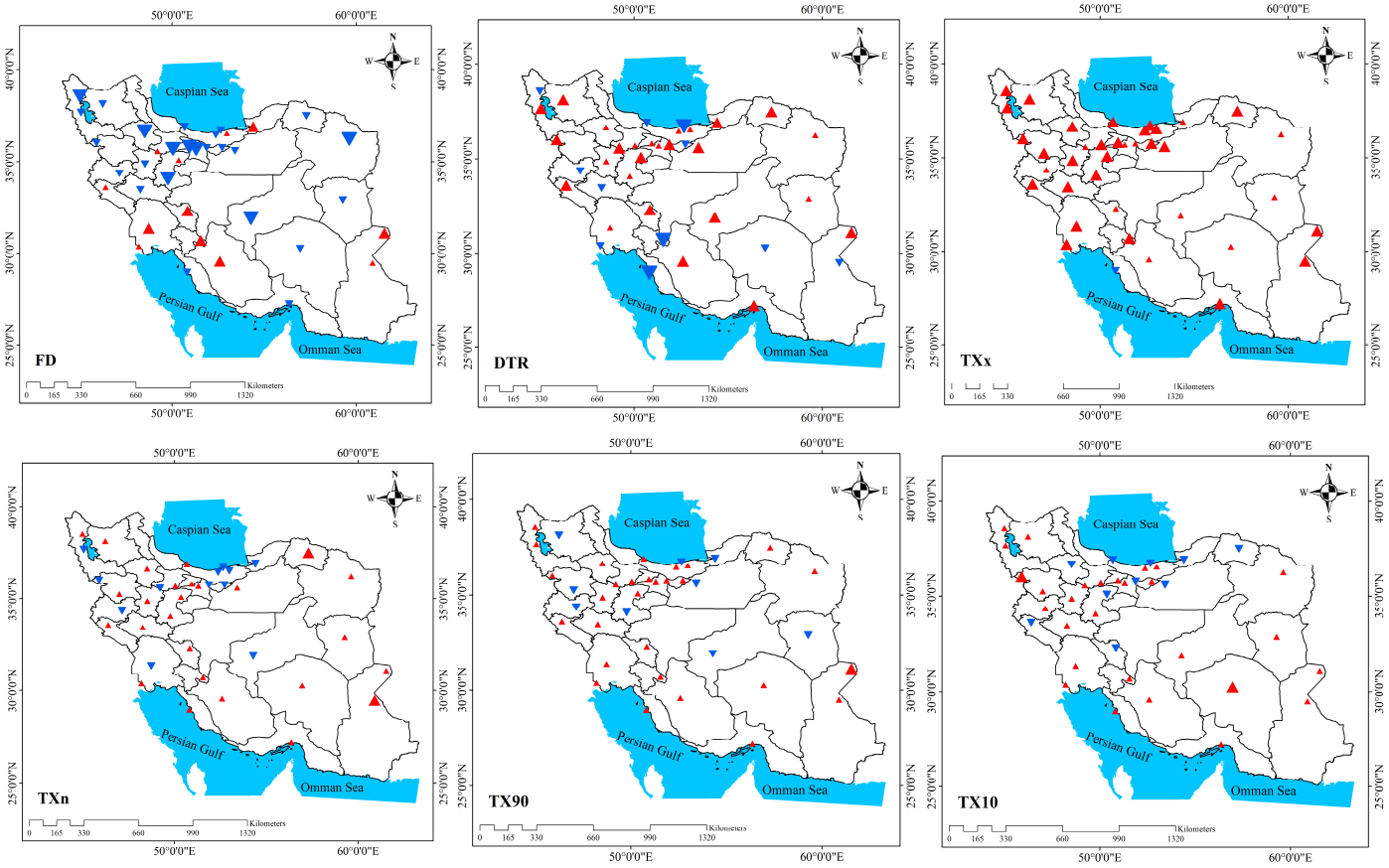


Figure 4. *Cont.*

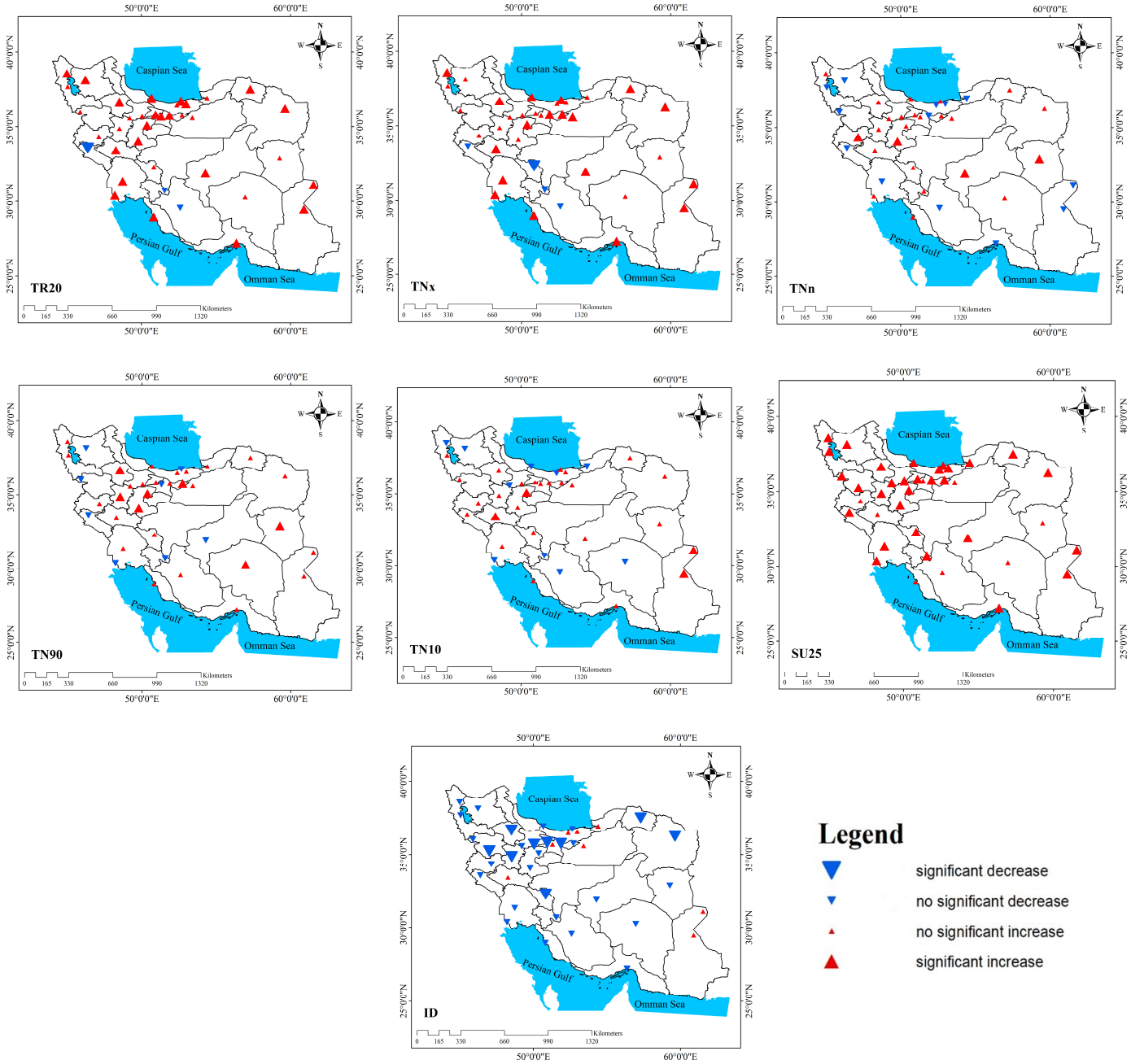


Figure 4. Spatial distribution of trends in temperature extreme indices in Iran from 1990 to 2020.

The TR20 index shows a significant increasing trend at all stations, except for Shiraz, Yasouj, and Ilam, where a significant decreasing trend is observed. The TNx index also shows an increasing trend at all stations except for four—Ilam, Shahrekord, Yasuj, and Shiraz. The TNn index has a significant increasing trend at most stations, with a few exceptions in the western and southeastern parts of the country. The TXn index shows an increasing trend at most stations, except those in the northern band and parts of the west. The TXx index has an increasing and significant trend across the country, except for the Bushehr statement. The TX10 index exhibits an increasing trend in most regions, except for the northern stations. The TX90 index shows an increasing trend at several stations and a decreasing trend at others; however, it has a predominant increasing trend at most stations.

In general, examining the trends of extreme indices in Iran indicates that all extreme indices, except for the FD and ID indices, have an increasing trend. These findings align

with those of other researchers, including [9,10,13–15], who reported a similar increasing trend in temperature extreme indices. This reinforces the consensus among these studies.

4. Conclusions

This study calculated 13 temperature extreme indices at 37 synoptic stations in Iran, based on daily maximum and minimum temperature data from 1990 to 2020. The Mann–Kendall trend test was employed to assess the trends of these indices. The results indicated an overall increasing trend in temperature extreme indices across Iran, suggesting warmer nights and an increase in the number of summer days. However, several indices, such as TN10, TNn, TX90, and TXn, exhibited a decreasing trend at various stations in the Zagros and northern regions of the country. Conversely, the two indices, FD and ID, showed a nationwide decreasing trend, indicating a reduction in frost and ice days. Analysis of the forward and backward graphs from the Mann–Kendall test revealed that all 13 indices were outside the confidence limit at the 0.05 level, confirming that the trends of all indices during the study period are significant.

Furthermore, the findings of this study indicate that the forward and backward graphs of the TNn and TXn indices intersected in 2009, indicating a mutation in that year, with the post-mutation trend slope being steeper than the pre-mutation slope. An examination of the Pearson correlation coefficients among the temperature extreme indices revealed that warm extreme indices positively correlate with one another, while cold extreme indices also show a positive correlation within their group; however, the correlation between cold and warm indices is negative. Decadal changes in extreme indices were calculated for three decades: 1990–2000, 2000–2010, and 2010–2020. The results demonstrate that temperature extreme indices generally increase in Iran, with the most significant rise occurring in the second and third decades, except for the SU25 index, which experienced its most significant change in the first and second decades. The two extreme indices, ID and FD, are on a downward trend, with a more pronounced decrease observed in the ID index. Overall, the findings of this study indicate variability in temperature extreme indices across different study stations; some stations exhibit a decreasing trend, while others show an increasing trend. Therefore, it is recommended that future research focus on calculating and examining the changes in the trends of these indices based on climatic classification or regional division according to elevation to achieve more reliable results concerning changes in these indices.

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