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ORIGINAL PAPER

An investigation on spatial and temporal trends in frost indices in Northern Iran

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Abstract

In this study, the trends of frost indices were investigated using the Mann-Kendall nonparametric test at 90% probability level. Frost indices, namely number of frost days (nFDs), number of frost-free days (nFFD), last spring frost (LSF), first fall frost (FFF), and growth season length (GSL), were obtained using minimum temperatures for 12 synoptic stations in the Caspian Sea coast, northern Iran. The statistical period of data ranged from 2000 to the end of 2018. Results showed an upward trend line for the nFDs index in western parts of the study area (Guilan province and part of Mazandaran province, with a significant downtrend at Rasht station as well). The nFDs index had a downward trend line slope in the eastern parts (Golestan province and part of Mazandaran province). Results of nFDs index at Gorgan station revealed a significant upward trend for the nFDs index. The nFFD index results were contrary to those of the nFDs index. The LSF index also presented a downtrend in the western part (Guilan province). Positive trend slopes were observed for the LSF index in the eastern regions (Golestan province and most of Mazandaran province). This index showed a significant uptrend at Astara station. Thus, the results of the LSF index indicate that LSF will occur earlier in the western regions and later in the eastern regions than previous periods. The FFF index also had a downtrend in the western part (the whole Guilan province and most of Mazandaran province), and the eastern part (Golestan province and a small part of Mazandaran province) experienced an upward slope. It should be noted that the FFF index had no significant trends in the study area. The uptrend and downtrend of this index indicate later and earlier occurrence, respectively, of FFF than normal situations. Finally, the GSL index, which represents the length of plant growth period, had a downtrend in the middle areas (Mazandaran province). The western (Guilan province) and the eastern (Mazandaran province) regions also had upward slopes. Also, no significant trends were observed for this index at all the stations.

1 Introduction

The most recent fifth assessment report (AR5) of working group of the Intergovernmental Panel on Climate Change (IPCC) concludes that globally, mean surface temperatures increased by 0.85 (range from 0.65 to 1.06) over the period 1880–2012. The measure of warming over the period 1951–2012 was about 0.72 (range from 0.49 to 0.89) (IPCC 2013). Most data also demonstrate that observed surface warming was associated with relatively larger increase in daily minimum night-time air temperature than daily maximum daytime air temperatures over the last 50 years. (Easterling et al. 1997; Hansen et al. 2012; IPCC 2013). Among other effects, the warming in minimum temperature since 1950s may have been associated with a change in frequency distribution of minimum temperature-related extremes, such as number of frost and frost-free days, last spring and first fall freeze dates, and growing-season length. The number of frost days can influence ecosystems, nature (Robeson 2002; Naganna et al. 2019), and human activities (Liu et al. 2008), and reflect severe climate change and climatic events over time (Meehl et al. 2007). Some of these changes influence the following factors: (1) prevalence of human and animal diseases, (2) changes in reproduction times of pests and insects, (3) species diversity in wetlands (Neustupa et al. 2011), (4) crop harvest (Pecetti et al. 2011), (5) seed production (Pons and Pausas 2012), (6) biomass production (Potithep and Yasuoka 2011), (7) plant photosynthesis (Oquist et al. 1993), (8) bird migration, (9) soil degradation and mineralization rate, and (10) hydrological processes (Biazar et al. 2019; Dinpashoh et al.

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Table 1 Literature review of frost indices and various definitions of a frost day

Indicator	Variables	Region	Time scale (period)	Source data	Equation	Reference
LSF	T_{min}	Valencia, Spain	(2002–2010)	81 stations	LSF = oak tree bud burst	(Pons and Pausas 2012)
FD, LSF, and FFF	T_{min}	France (Mt. Ventoux)	Daily (2006–2007)	7 stations	FD = $T_{min} < 0$ °C	(Davi et al. 2011)
FD, nFD	T_{min}	Turkey	Daily (1950–2010)	72 stations	FD = $T_{min} < 0$ °C	(Erlat and Türkeş 2011)
FD	T_{min}	Korea	Daily (1980–2011)	66 stations	FD = $T_{min} < 0$ °C	(Kim et al. 2011)
FD	T_{min}	Czech Republic (swamp area)	Daily (12 May 2008–19 May 2010)	2600 different species	FD = $T_{min} < 0$ °C	(Neustupa et al. 2011)
Mean nFD	T_{min}	Mediterranean	Daily	6 stations	Not specified	(Pecetti et al. 2011)
FD	T_{min}	Japan	Daily (2001–2006)	2 stations	FD = $T_{min} < 2$ °C	(Potithep and Yasuoka 2011)
FD	T_{min}	Scandinavia, northern Poland, and Germany	Daily (1961–1990)	554 stations	FD = $T_{min} < 0$ °C	(Rojas et al. 2011)
FD	T_{min}	North America	Daily (1951–2010)	17,000 stations	FD = $T_{min} < 0$ °C	(Terando et al. 2011)
FD, GSL	T_{min}	Entire China	1961–2003	303 stations	FD = $T_{min} < 0$ °C	(You et al. 2011)
FD	T_{min}	Mainland China	Daily (1961–2008)	526 stations	FD = $T_{min} < 0$ °C	(Zhou and Ren 2011)
FD, frost hours	T_{min}	Island of Majorca	Daily and hourly (1972–2008)	8 stations	FD = $T_{min} < 0$ °C	(Cuxart and Guijarro 2010)
Ground frost days	T_{min}	35 states in the USA	1964–2004 (humans) 1963–2005 (animals)	35 state regional values	FD = $T_{min} < 0$ °C	(Nakazawa et al. 2010)
FD	T_{min}	54 accessions from 12 Israeli populations	Daily (November–April) 2002–2005	450 independent species from 52 regions	Region-specific	(Ben-David et al. 2010)
FD	T_{min}	South America	Daily (1950–2003)	41 stations	FD = $T_{min} < 0$ °C	(Rusticucci et al. 2010)
FD	T_{min}	Southern China	Daily (1990–2008)	1 station	FD = $T_{min} < 0$ °C	(Zhao et al. 2009)
FD	T_{min}	Africa (areas with disease of monkey pox)	More of a theory	Monkey pox–infected areas thoroughout Africa (theory)	FD = $T_{min} < 0$ °C	(Levine et al. 2009)
FD, frost-free season	T_{min}	China	Daily (1955–2000)	305 stations	FD = $T_{min} < 0$ °C	(Liu et al. 2008)
FD, FFD, GSL	T_{min}	Contiguous USA	Daily (1950–2000)	0.5° × 0.5° grid	FD = $T_{min} < 0$ °C	(Feng and Hu 2004)
FD	T_{min}	Worldwide	Daily (1961–1990, some regions 1950–1995)	2.5° × 3.75° grid	FD = $T_{min} < 0$ °C	(Kiktev et al. 2003)
FD, LSF, FFF, and GSL	T_{min}	Illinois, USA	Daily (1906–1997)	36 stations	Hard freeze FD = $T_{min} <- 4.4$ °C FD = $T_{min} <- 2.2$ °C FD = $T_{min} < 0$ °C cold-sensitive plants (e.g., warm-season vegetables) FD = $T_{min} < 5.6$ °C	(Robeson 2002)
FD, GSL	T_{min}	Worldwide	Daily (varies with country)	Station (no. not specified)	FD = $T_{min} < 0$ °C	(Peterson et al. 2001)
FD, nFD	T_{min}	Netherlands	Daily (1975–2000)	Royal Dutch Metrological Institute	FD = $T_{min} < 0$ °C From December 1–March 1	(Visser and Holleman 2001)
FD, LSF, and FFF	T_{min}	Contiguous USA and Canada	Daily (1959–1993)	700–800 stations	FD = $T_{min} < -2.2$ °C	(Schwartz and Reiter 2000)

FD frost day, *nFD* number of frost days, *LSF* last spring frost, *FFF* first spring frost, *GSL* growing-season length

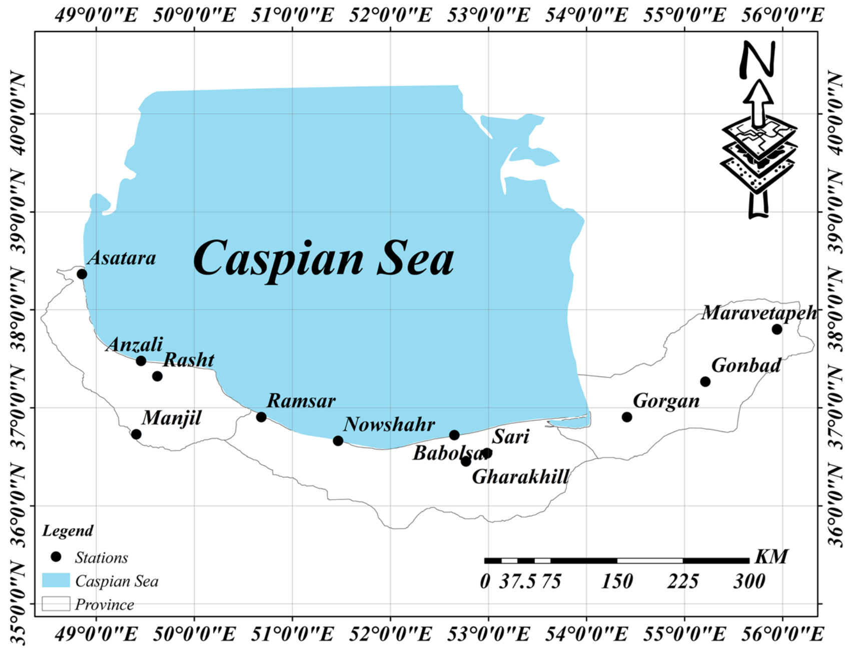


Fig. 1 Location of the study area and the selected stations

2019; Ashrafzadeh et al. 2020). Since the early 1980s, scientific interest in frost indices has increased because they are important indicators of climatic change, and frost has outward impacts on socioeconomic sectors including agriculture, energy production and utilization patterns, and natural ecosystems (Erlat and Türkeş 2016). Systematic changes and natural variations in growing-season length and associated freeze-date statistics have important implications for natural and managed ecosystems. Many plants and insects are particularly sensitive to the timing of extreme cold events at the beginning and end of the growing season. Also, many studies have shown significant alterations in the timing of leaf unfolding as a response to climatic warming (Schwartz 1998; Menzel and Fabian 1999; Walther et al. 2002; Cleland et al. 2007). Variations in growing-season length and the timing of freeze events can also be an important indicator of climatic change that may not be represented in mean conditions. However, there are a wide variety of extreme events, and their impacts can be highly variable. Thus far, a number of indices have been used to assess the impact of frost on agriculture, including the time of first frost day in autumn and winter every year, the number of successive frost days, and the duration of frost-

Table 2 The geographical coordination of the stations

Name	*Y* (degree)	*X* (degree)	Elevation (m)	The mean value of minimum temperature °C	Precipitation (mm/day)	Evaporation (mm/day)
Anzali	37.48	49.46	− 23.6	14.51	4.67	2.67
Asatara	38.37	48.85	− 21.1	12.28	3.50	2.52
Rasht	37.32	49.62	− 8.6	12.61	3.24	2.34
Manjil	36.73	49.41	338.3	13.05	0.52	6.82
Babolsar	36.72	52.65	− 21	14.71	2.24	2.57
Gharakhill	36.45	52.77	14.7	12.88	1.65	2.97
Sari	36.54	52.99	23	13.63	1.83	3.05
Nowshahr	36.66	51.47	− 20.9	12.73	3.19	2.92
Ramsar	36.90	50.68	− 20	14.04	3.04	2.80
Gonbad (Gonbad-Kavus)	37.27	55.21	37.2	12.88	1.11	3.79
Gorgan	36.91	54.41	0	12.67	1.18	3.98
Maravetapeh	37.80	55.94	460	13.54	0.81	6.30

free days, which are some common climate indices in crop production. Changes in the growing-season length and the time of frost incidence can also be important climatic indices that may not be considered in average conditions (Robeson 2002). This research seeks to examine variations in last spring freeze, first fall freeze, and growing-season length under the influence of climate change and their effects on agriculture.

It should be noted that the geographical and temporal details of frost indices can be useful in updating temporal, regional, and local crop planting recommendations and management decisions on water resources. Guilan, Mazandaran, and Golestan coastal provinces with temperate climates are the most important agricultural provinces of Iran. Therefore, changes in frost indices can reflect climatic and hydrologic changes in these areas.

A bulk of research has already focused on frost day indices. Anandhi et al. (2013) investigated long-term spatiotemporal trends of frost indices in Kansas, USA. They used five frost indices, namely number of frost days (nFDS), number of frost-free days (nFFD), last spring frost (LSF), first fall frost (FFF), and growth season length (GSL), and reported that minimum temperatures generally increased during the statistical period, leading to decreased nFDS. LSF and FFF occurred earlier and after their normal states per year, respectively, resulting in an increased trend in GSL. Darand et al. (2015) studied the spatiotemporal trend of temperatures in Iran using the Mann-Kendall and linear regression methods to investigate the annual temperature trend. They observed an increase in the frequency of maximum temperatures but a negative trend in minimum temperatures. Erlat and Türkeş (2016) investigated frost start date, frost ending date, and frost-free seasons in Turkey using three frost indices of FFF, LSF, and LFF obtained by minimum temperatures. They found that LSF and FFF occurred earlier and later, respectively, and the GSL index had a rising trend.

Rahimi and Hejabi (2018) examined temperature routing indices using 33 synoptic stations in Iran for the period 1960–2014. They observed significant warming trends of temperature indices at most stations, particularly at minimum temperature indices. At low altitudes, the indices represented warm climates, but positive and negative trends were detected for temperature indices at high altitudes. Studies conducted in this field have been summarized in a one-list Table 1, which can be referred to for further information.

A number of researchers have studied variations of these indices in other regions (Table 1). Yet, no research has investigated the trend of frost days with the mentioned indices in the three provinces above. This study, therefore, aims to investigate changes of trends in frost indices, number of frost days (nFDs), number of frost-free days (nFFDs), last spring freeze (LSF), first fall freeze (FFF), and growing-season length (GSL).

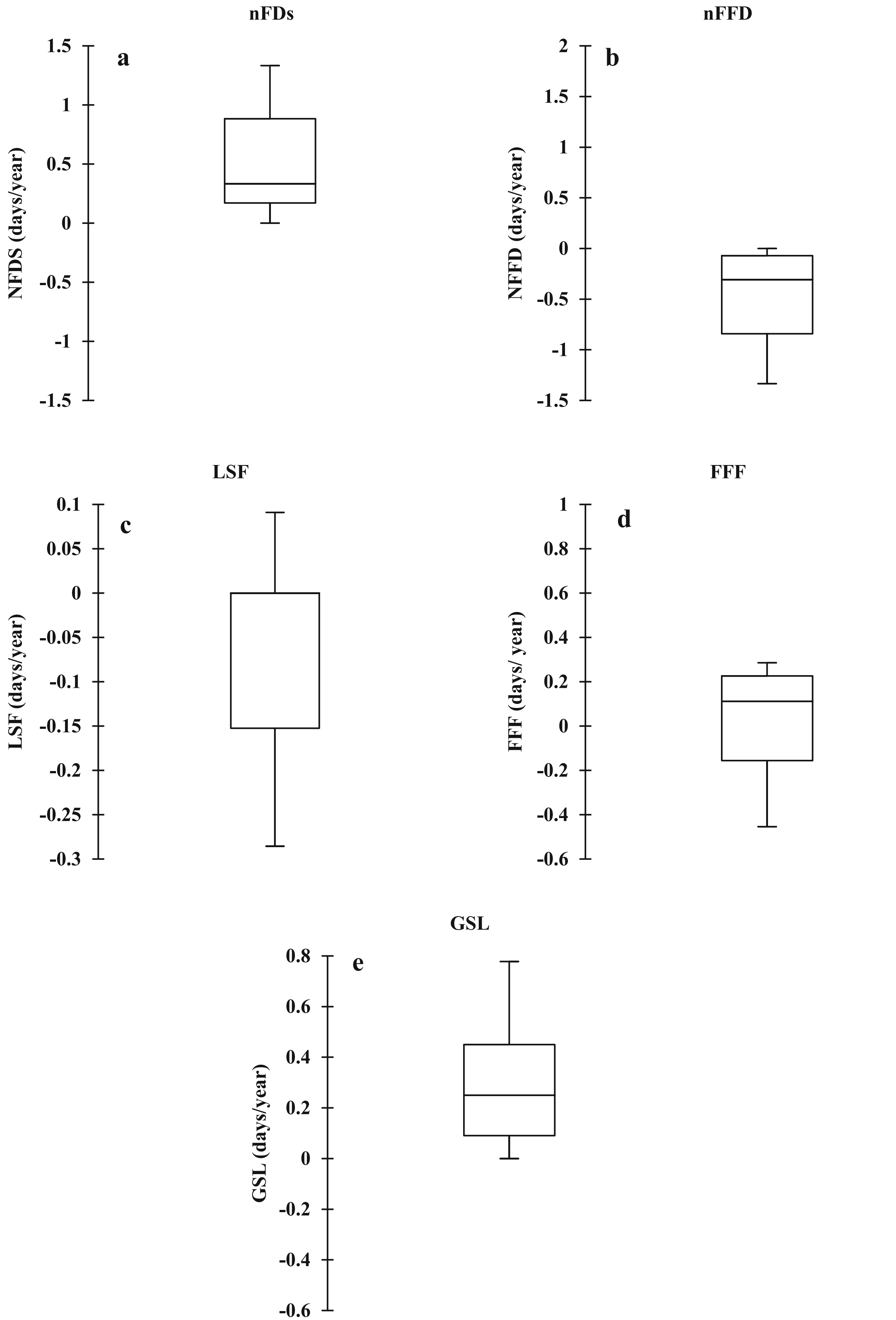
Fig. 2 Box plots of trend slopes for the five frost indices. The lower and upper ends of the box define the 25 and 75 percentile values; the line inside the box demonstrates the median; and the whiskers show 5 and 95 percentile values. **a** nFDs (days/year). **b** nFFD (days/year). **c** LSF (days/year), **d** FFF (days/year). **e** GSL (days/year)

2 Materials and methods

2.1 Study area

Three provinces of Guilan, Mazandaran, and Golestan, located along the Caspian Sea coast as a narrow strip in the north of Iran, were selected for analyses. The coordinates of the region lie approximately between latitudes 36° to 38° 30′ N and 48° to 56° E (Fig. 1). West Alborz, like a fence, covers Guilan province. The plains of Guilan province lie between the sea and the mountains, up to 100 m above sea level. The climate of Guilan is known as the temperate Caspian climate. The Talesh Mountains with north-south direction and Alborz Mountains along the west-east act as a barrier preventing the passage of the Caspian Sea water and the northwestern wet winds into Iran due to high altitude cause heavy rainfall in Guilan province (Isazadeh et al. 2019). Increased evaporation over Caspian Sea increases air humidity (up to 93%, especially during the warmer months), adjusts the air temperature in summer, and reduces it in winter, especially in lowland areas near the sea. Therefore, the winter frost near the seaside has been very low. Guilan province is predominantly covered by tall forest trees and has a humid climate with hot and humid summers and mild winters (Isazadeh et al. 2017; Biazar et al. 2018; Dinpashoh et al. 2019; Ashrafzadeh et al. 2019; Khaledian et al. 2020;).

The natural position of Mazandaran province indicates two major areas of Alborz coastal and mountainous plains. Along the Alborz Mountain range, a long and tall wall encloses the coastline plains of the Caspian Sea. Throughout Mazandaran province, the slope and elevation of the land decline from altitudes toward the plain to the Caspian Sea. Two major factors play a decisive role in the provincial climate. One is the north and northeast airflow that runs from Siberia and the Arctic to the south and southwest, causing cold, frosty, and snowy weather. This air mass is driven north in summer and has little effect on the climate of Mazandaran. The other one is the airflow of western winds that cross the Atlantic Ocean, the Mediterranean Sea, and the Black Sea in winter, causing heavy and persistent rainfall upon entering Iran. According to the temperature and precipitation, the climate of Mazandaran province is divided into temperate Caspian climate, temperate mountainous climate, and cold mountainous climate. Mazandaran province climate is similar to Guilan, including the mild and humid climate of Caspian shoreline and the moderate and cold climate of mountainous regions. The terrain of Golestan province is such that it can be divided


nFDs
a
NFDS (days/year)
1.5
1
0.5
0
-0.5
-1
-1.5
nFFD
b
NFFD (days/year)
2
1.5
1
0.5
0
-0.5
-1
-1.5
LSF
c
LSF (days/year)
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
FFF
d
FFF (days/ year)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
GSL
e
GSL (days/year)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6

into plains and mountainous parts. Along the Alborz Mountain range, the coastline and coastal plains are enclosed by a long wall; as a result, the slope decreases from altitudes toward the plain and the Caspian Sea (from north to south towards south coasts and from east to west towards the east coast of the sea) almost throughout the province. Depending on its geographical location, Golestan province is affected by latitude, longitude, and Alborz Mountain range, elevation, distance and proximity to the sea, southern deserts of Turkmenistan, local and regional winds, and dense forest cover. For this reason, it has a variety of climates with low width contrary to the general opinion that the climate is generally temperate (The Islamic Republic of Iran, Meteorological Organization; http://www.irimo.ir/). The climate of Golestan is mild and temperate most of the year. This province is geographically located in the east part of study area (Fig. 1). Four, five, and three stations were studied from Guilan, Mazandaran, and Golestan, respectively (Fig. 1). Table 2 shows the geographical characteristics of the selected stations.

2.2 Definitions of indices

There are multiple definitions of frost day in the literature. In the majority of studies, frost day is defined as a day when minimum temperature is below a base temperature (T_b); the value of which is optional and some are listed in Table 1. The most common value for T_b is 0 °C (Anandhi et al. 2013), but appropriate temperatures for plants vary depending on the plant characteristics, and damage to the plant depends on the degree and severity of frost (Christidis et al. 2007). Therefore, a range of T_b for frost day is defined as − 4.4 °C, − 2.2 °C, and 5.6 °C (Robeson 2002); 2.2 °C (Schwartz and Reiter 2000; Goodin et al. 2003); and 2 °C (Potithep and Yasuoka 2011). Given the climatic and coastal situations, as well as the plants grown in the three provinces, a temperature of 5.6 °C was considered the T_b in this study (Robeson 2002; Biazar et al. 2019; Aghelpour et al. 2019).

1. nFDs: nFDs is defined as the total number of days with minimum temperature ≤ T_b °C between the first frost day in autumn and the last frost day in spring.
2. nFFD: nFFD is defined as the total number of days with minimum temperature > T_b °C between the first frost day in autumn and the last frost day in spring.

Both the nFDS and nFFD can be estimated monthly, seasonally, and annually.

3. LSF: Last spring freeze (LSF) is defined as the last day in March through May with minimum temperature < T_b °C (the first day between this period with minimum temperature < T_b °C) (for the last time until fall).
4. FFF: First fall freeze (FFF) is a day between September and November with minimum temperature < T_b °C for the first time since spring, (the first day between this period with minimum temperature < T_b °C).
5. GSL: Growing-season length (GSL) has been defined differently in the literature, but it is generally based on the beginning of spring and autumn (fall) (GSL is based on the onset of spring and fall). If the focus is more on vegetation growth than flexibility, temperature thresholds above 10 and 6.1 °C are considered for spring onset and end of autumn, respectively (Christidis et al. 2007). Growing-season length variations also are closely related to variations in overall seasonality, which are an important component of recent climate change research. According to Davis (1972), the number of days between LSF and FFF per year represents the GSL (Robeson 2002; Anandhi et al. 2013).

2.3 Trend analysis

In this study, the nonparametric Mann-Kendall method (Mann 1945; Kendall 1975) was applied for five time series. One of the main problems with process testing in a given dataset is the impact of serial correlation of data. The modified version of Mann-Kendall method, introduced by Yue et al. (2002), eliminates the effect of lag-1 serial correlation (r_1) on the data. If there is a serial positive correlation in data series, the nonparametric test presents a significant trend over a time series, which is in fact randomly more than what was specified by the test. To eliminate the effect of serial correlation, therefore, the value of r_1 was calculated for all-time series at 10% significance level. To this end, the absolute value of r_1 was compared with important thresholds depending on the number of data and the level of significance. If r_1 is greater than the critical value at a given significance level (90% here), the null hypothesis is then rejected, and the alternative hypothesis (i.e., r_1 being statistically significant at 90% probability level) is accepted; otherwise, the null hypothesis is accepted and the alternative hypothesis is rejected. Therefore, the effect of serial correlation is eliminated with this method before using the Mann-Kendall method. For more information, one can refer to Dinpashoh et al. (2011), Yue and Wang (2004), and Dinpashoh et al. (2019).

2.4 Theil-Sen's estimator

The Sen's estimator is a nonparametric approach with a very close relation to the Mann-Kendall method (Tabari et al. 2012; Dinpashoh et al. 2019). The n even slope of data was

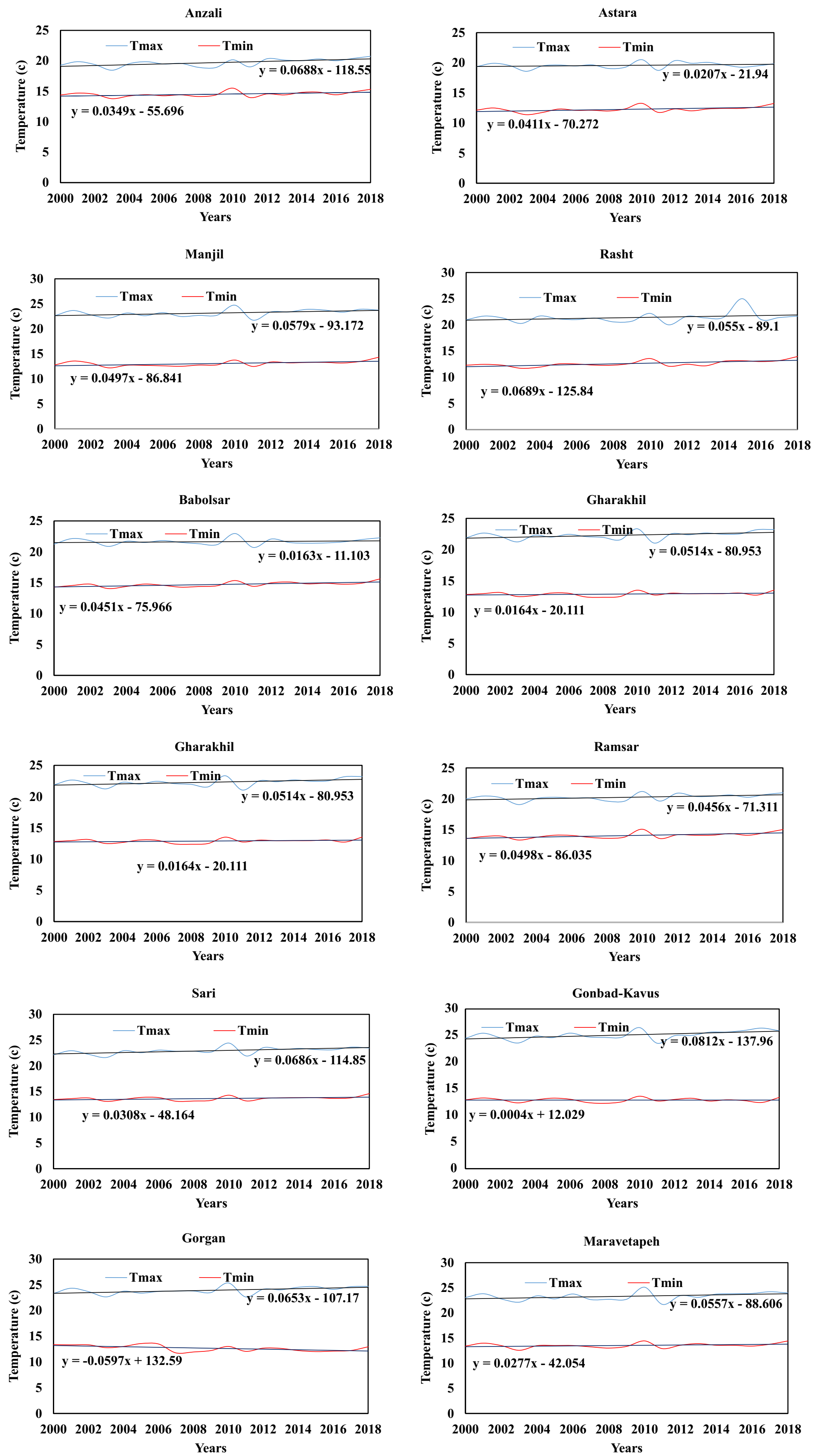


Fig. 3 Variation of minimum and maximum temperature in the selected stations

calculated using this method (Sen 1968; Dinpashoh et al. 2011) by the following equation:

$$\beta = \text{Median}\left(\frac{(x_i - x_l)}{j - l}\right) \quad \forall 1 < l < j \tag{1}$$

2.5 Spatial analysis of temperature series

This method is used to map the slope of the trend line of the indices nFDs, nFFD, FFF, and GSL based on the assumption that the effect of one parameter on the points around it is not the same at an intermediate level and the effect will be less with further the distance from the source. The electric field E (x,y) is the value interpolated by the following formula (Lu and Wong 2008; Achilleos 2011; Dinpashoh et al. 2019; Meshram et al. 2020).

$$E(x, y) = \sum_{j=0}^{n} w_j E\left(x_j y_j\right) \tag{2}$$

where (x_j, y_j), (x, y), and w_j are the coordinates of the scattering points, the interpolation points, and the weight function, respectively.

3 Results

Figure 2 shows box plots of slope trend lines for frost indices using 19-year data in three provinces of Guilan, Mazandaran, and Golestan. According to the figure, mean slope values are positive for all indices, except the nFFD, and zero for the LSF. Mean slope values for nFDs, nFFD, FFF, and GSL indices are 0.34, − 0.31, 0, 0.12, and 0.25, respectively. The negative value of the nFFD index indicates that the median slope of the trend line is decreasing for frost-free days (according to the scale) in the study area. The positive value for the nFDs index denotes an uptrend line slope of the nFDs in the study area, indicating a rising trend in the number of cold days.

The obtained positive value for the FFF index reveals the later occurrence of the FFF. The results of the LSF index suggest no significant changes. The positive median slope trend line for the GSL index indicates that the GSL has an increasing trend in the study area.

Figure 3 displays changes in maximum and minimum temperatures at the studied stations. An upward trend is observed for maximum temperatures at all stations. An uptrend for minimum temperatures is maintained at all stations, except in Gorgan.

As shown in Fig. 3, maximum trend line slope (0.0812) belongs to Gonbad (Gonbad-Kavus) station. On the other side, the highest trend line slope for minimum temperatures is observed in Rasht station. The lowest slope (0.0163) for maximum temperature was recorded in Babolsar station. Minimum temperature in Gorgan station has the least trend line slope of − 0.059.

Fig. 4 Spatial distribution of trend results for the period (2000–2018) for the Guilan Province. **a** nFDs. **b** nFFD. **c** LSF. **d** FFF. **e** GSL. Downward (upward) pointing hollow triangles indicate the location of stations with decreasing (increasing) trend, and the downward (upward) pointing black-filled triangles indicate the location of stations with decreasing (increasing) trend (both at the 90% significance level). The open circles indicate the location of stations with zero Z statistics (i.e., no significant trend in any significance level)

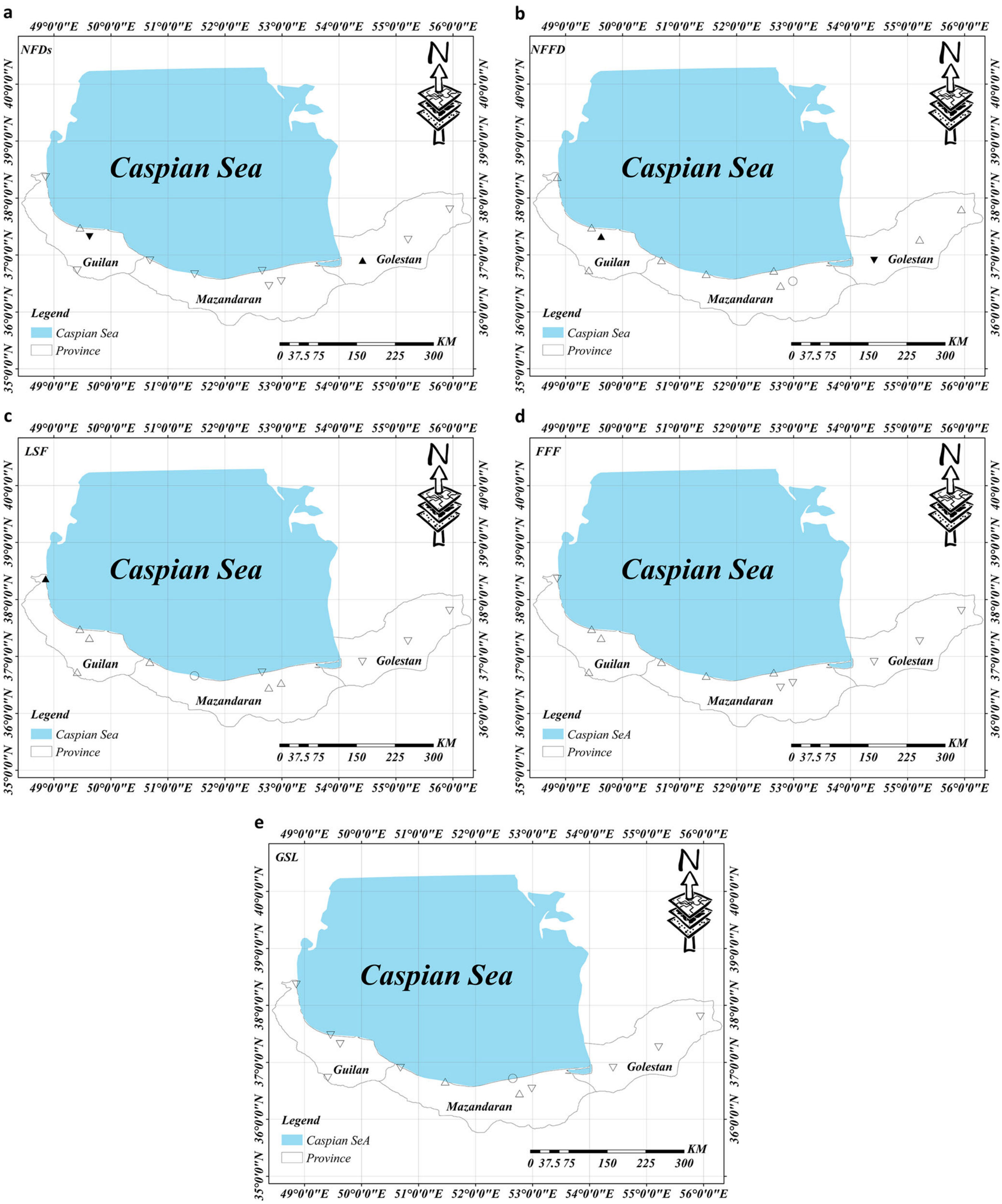
The spatial distribution of the trends for the five frost indices is shown in Fig. 4. According to Fig. 4a, the nFDs index shows a significant trend in only two stations, with significant upward and downward trends in Gorgan and Rasht stations, respectively. A non-significant rising trend is noticed for the nFDs index at one out of 12 stations. It is noteworthy that the nFDs index had a non-significant downtrend in the rest of stations.

Figure 4 b depicts the nFFD index trend indicating almost converse results to those of nFDs, with Rasht and Gorgan stations showing significant upward and downward trends, respectively. In addition, a non-significant uptrend is visible for this index at all stations, except in Sari. Figure 4 b shows that Sari station has no trends for the nFFD index.

According to Fig. 4c, the LSF index shows rising trends at four stations in Guilan province. One out of four stations in Guilan province showed significant uptrends for the LSF index. Trend analysis for this index showed a non-significant falling trend at all three stations in Golestan province. There was no trend for this index at Nowshahr station in Mazandaran province, with non-significant rising trends in Ramsar, Sari, and Gharakhill stations. Babolsar station presented a falling trend for the LSF index.

At all the 12 stations, no significant trends were observed for the FFF index (Fig. 4d), with a non-significant upward trend in Mazandaran province for the three near-shore stations (Babolsar, Nowshahr, and Ramsar). The trend of FFF index was downward in the other two stations (Sari and Gharakheil) out of five stations in Mazandaran province. As with the LSF index in Golestan province, the FFF index showed a downward trend at three stations (Gorgan, Maravetapeh, and Gonbad). The FFF index had a rising trend at three stations (Anzali, Rasht, and Manjil) of four stations in Guilan province, and a non-significant downward trend in one station (Astara).

Based on the GSL index trend in three provinces of Guilan, Mazandaran, and Golestan (Fig. 4e), the three stations in Golestan province represent a downtrend in this index. The four stations of Guilan province (Rasht, Manjil, Astara, and Anzali) showed a downward trend for this indicator. Of five stations in Mazandaran province, one station (Babolsar) had no trend for the GSL index. Two stations (Gharakhill and Nowshahr) showed a rising trend in this index. The other


a
NFDs
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NFFD
c
LSF
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GSL
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35°0'0"N 36°0'0"N 37°0'0"N 38°0'0"N 39°0'0"N 40°0'0"N
N
Caspian Sea
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0 37.5 75 150 225 300
KM

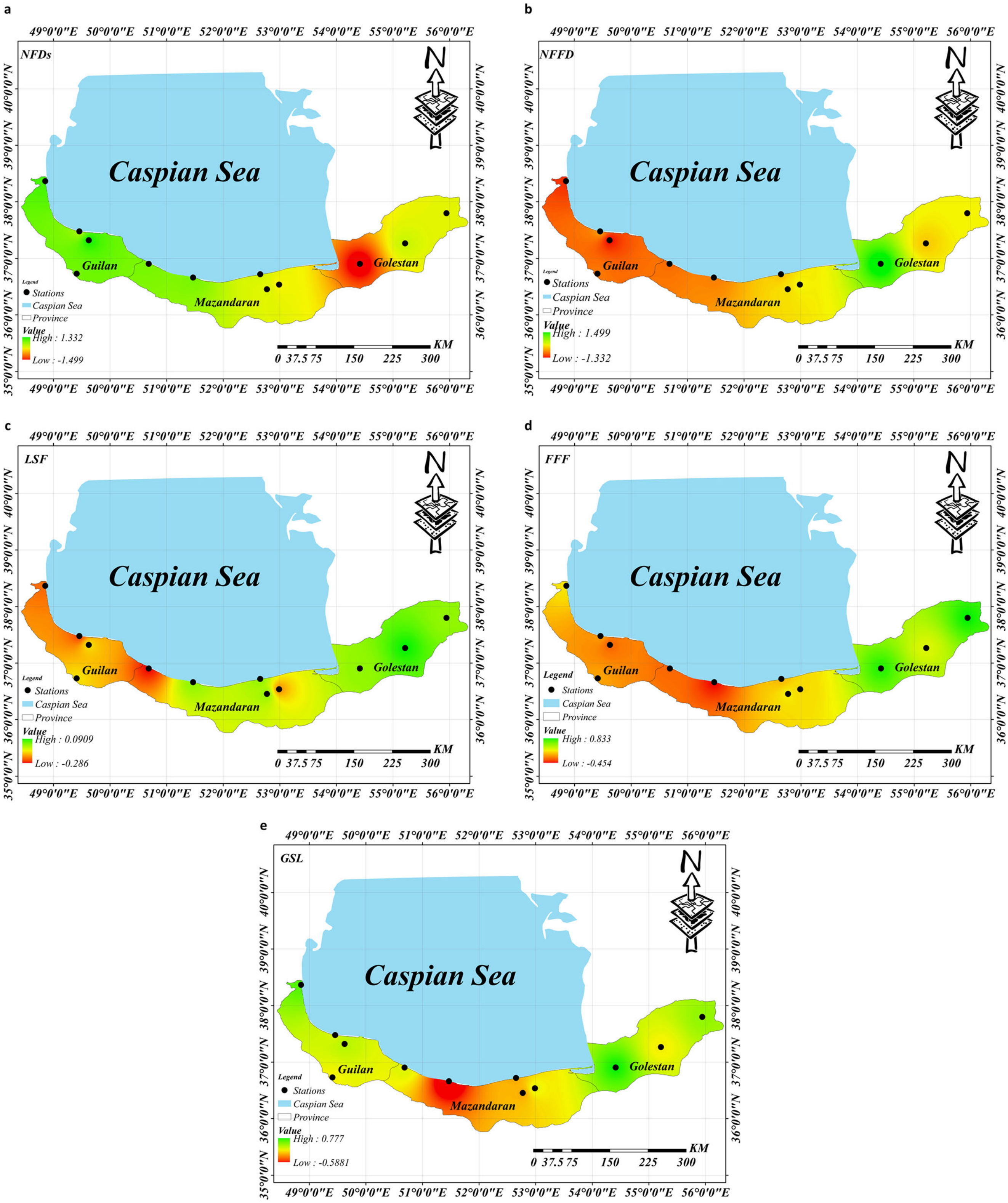

Fig. 5 Spatial distribution of trend slopes for 19 years (2000–2018). **a** nFDs (days/year). **b** nFFD (days/year). **c** LSF (days/year). **d** FFF (days/year). **e** GSL (days/year)

two stations (Sari and Ramsar) in Mazandaran province showed a descending trend for the GSL index.

Figure 5 illustrates the spatial distribution of the trend line slopes for the five frost indices, with red and green indicating negative and positive trends, respectively, for the frost indices. An upward trend line slope is observed for the nFDs index in the western and central parts of the study area, encompassing the whole Guilan province and most of Mazandaran province (Fig. 5a). The eastern part of the region (Golestan province) shows a downward trend line slope for the nFDs. As shown in Fig. 5a, the trend line slope varies between 1.332 and − 1499 for the nFDs index, with the highest and lowest values recorded in Rasht and Gorgan, respectively. According to Fig. 5a, the nFDS will increase in the areas where there is an uptrend slope of the nFDs index (western of the study area), whereas the nFDS dropped in areas with downtrend slopes (eastern and central parts of the study area). Figure 5 b exhibits the trend line slope for the nFFD index, showing contrary results for this index to those of the nFFDs index. In the eastern part of the region, there is an uptrend slope, with Gorgan station presenting the highest value (1.5) for this index. The trend line slope is slightly increasing at the other two stations (Gonbad and Maravetapeh) in Golestan province. A decreasing trend line of the nFFDs index is noticed in the western part of the study area, including the whole Guilan province and parts of Mazandaran province.

Figure 5 c reveals a decreasing trend line slope for the LSF index in the western regions; hence, the LSF occurs earlier in these areas. The trend line slope was mainly upward in the central and eastern regions. It should be noted that the trend line in Golestan province is sharper than that in Mazandaran province (Fig. 5c). For the LSF index (Fig. 5c), the highest and the lowest values were 0.09 and − 0.28 in Gonbad and Ramsar stations, respectively. As it can be seen from Fig. 5, the LSF slope values are lower than the other indices.

The trend line slope of the FFF index (Fig. 5d) represents a negative trend slope in the western part of the study area (Guilan province and almost most part of Mazandaran province), except in Astara where the FFF slope value is positive because this station is located nearby mountain areas. This negative trend suggests that early fall cold will occur in these areas. However, the index has a positive trend in eastern parts (Golestan province and a small part of Mazandaran province), indicating later occurrence of fall cold than the past periods. The FFF slope values varies between − 0.454 and 0.833 for Nowshahr and Maravetapeh, respectively. As it can be seen in Fig 5 c and d, the FFF trend slope values are sharper than those of the LSF. An increasing trend is observed for the GSL index in Guilan and Golestan provinces (Fig. 5e). However, the trend line slope was downward for this index in the middle parts of Mazandaran province. In the western and eastern regions, therefore, an increase will occur in the GSL index.

4 Conclusion

In this study, the trends of frost indices were investigated using the Mann-Kendall nonparametric test at 90% probability level. Frost indices, namely number of frost days (nFDs), number of frost-free days (nFFD), last spring frost (LSF), first fall frost (FFF), and growth season length (GSL), were obtained using minimum temperatures for 12 synoptic stations in the Caspian Sea coastline. The trend line slope for maximum temperatures has maintained an uptrend at all stations. Minimum temperatures also presented rising trends at all stations except in Gorgan station. It should be noted that a mild trend line slope was obtained for maximum and minimum temperatures at all studied stations. The results indicate low values obtained for the trends of frost indices, suggesting slight changes in the trends of indices. The calculated trend values were not significant for almost all indices at most stations, leading to different results in the trend line slopes compared with those of studied indices. Also, no trends were observed for nFFD, LSF, and GSL indices in Sari, Nowshahr, and Babolsar stations, respectively.

Results showed an upward trend line for the nFDs index in western parts of the study area (Guilan province and part of Mazandaran province), with a significant downtrend at Rasht station as well. The nFDs index had a downward slope in the eastern parts (Golestan province and part of Mazandaran province). Results of nFDs index at Gorgan station revealed a significant uptrend for the nFDs index. The nFFDs index results were contrary to those of the nFDs index. The LSF index also presented a downtrend in the western part (Guilan province). Positive trend slopes were observed for the LSF index in the eastern regions (Golestan province and most of Mazandaran province). This index showed a significant uptrend at Astara station. Thus, the results of the LSF index indicate that LSF will occur earlier in the western regions and later in the eastern regions than previous periods. The FFF index also had a downtrend in the western part (the whole Guilan province and most of Mazandaran province), and the eastern part (Golestan province and a small part of Mazandaran province) experienced an upward slope. It should be noted that the FFF index had no significant trends in the study area. The uptrend and downtrend of this index indicate later and earlier occurrences, respectively, of FFF than normal situations. Finally, the GSL index, which represents the length of plant growth period, had a downtrend in the middle areas (Mazandaran province). The western (Guilan province) and the eastern (Mazandaran province) regions also had upward slopes. No significant trends were observed for this index at all stations. Positive values were obtained for median trend line slopes of the three frost indices, with only a negative value for the nFFD index trend line. The LSF index had a zero median trend line slope.

For frost days in fall (autumn) and winter seasons, increasing the slope for nFDs in the western regions of the study area indicates that the number of frost days has increased in these two seasons. Also, due to the descending slope of the line for the LSF index, the occurrence date of the LSF day occurred earlier in the western regions. It should be noted that the decreasing trend slope of this index is more visible in Guilan province. This means that the date of the LSF day will tend to winter, that is, the LSF day will be observed sooner in Guilan region. In the middle and eastern parts of the study area, the date of LSF will occur later due to the increasing slope of the LSF trend line, that is, the frequency of occurrence in these areas is more prone to spring, which will damage the gardens in these areas. It should be noted that these changes will not be noticeable due to the low value of slope for this indicator. In the western regions, the FFF index also has a descending slope (except in Astara station). To the east of the study area, the slope for this indicator shows an upward trend. Therefore, the occurrence date of the FFF index will be earlier in the western and middle regions, meaning that the occurrence date of the FFF will be observed earlier. Moving eastward, the occurrence date of the FFF will occur later due to the upward slope in these areas, which tends to be in winter. The delay in the occurrence of the FFF index and the increase in the nFFD in the eastern areas of the study area have caused some trees to bloom in fall, which is harmful and weakens the trees (Islamic Republic of Iran, Ministry of Agriculture; https://www.maj.ir/).

Considering the comparison between FFF and LSF indices and the growth period in the study area (spring and summer), it is suggested to slightly delay the cultivation date in the eastern study areas and also have a slightly earlier cultivation date in the middle regions, especially in the western regions of the study area. It should be noted that the slope values of the FFF index were sharper than that of LSF, which means that the former was more effective in determining the cultivation period. Therefore, the cultivation date of crops should be determined in such a way that the growth period or harvest date in these areas is not exposed to the cold season in the fall. As mentioned above about the GSL index, the last occurrence date of the LSF occurred in the middle of the study area, i.e., the occurrence date of this day was more inclined to spring, and the date of the FFF was earlier in the middle regions. Therefore, the length of the cultivation period will decrease in this area, indicating that the cultivation date must be changed and crops may not be traditionally grown, which result in lower yields. Unlike the middle region, an increase in the cultivation period is observed in the western (Guilan province) and eastern (Golestan province) areas where more diverse plants can, therefore, be cultivated according to climatic conditions. Increased length of the cultivation period can lead to premature planting, and also guarantees the maturity and availability of multiple crops (subject to availability of water resources). An increase in the length of the growing period can be especially useful for perennial crops, but it may increase the damage caused by plant diseases and insects. According to the findings, this research can be very helpful in hydrologic and agronomic issues in these areas.

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