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Saeed Sharafi (s-sharafi@araku.ac.ir)
assistant professor at Arak University, Arak, Iran
Mehdi Mohammadi Ghaleni
Arak University

Research Article

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Posted Date: August 26th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-835261/v1

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Version of Record: A version of this preprint was published at Theoretical and Applied Climatology on November 24th, 2021. See the published version at https://doi.org/10.1007/s00704-021-03853-0.

Spatial assessment of drought features over different climates and seasons across Iran

[*1]Saeed Sharafi, [2]Mehdi Mohammadi Ghaleni

1. Assistant Professor, Department of Environment Science and Engineering, Arak University, Arak, Iran.

2. Assistant Professor, Department of Water Science and Engineering, Arak University, Arak, Iran.

Corresponding author: Saeed Sharafi
Corresponding email: s-sharafi@araku.ac.ir
Telefax: +988632623702

Abstract

Drought is one of the most complex phenomena in the world, so proper management is very important in monitoring and reducing its damage. For this purpose, Standard Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI) and Reconnaissance Drought Index (RDI) indices were used to analyze the intensity and frequency of drought in the coastal wet, mountain, semi mountain, semi desert, desert and coastal desert climates of Iran in four seasons, separately: autumn, winter, spring and summer. 43 synoptic stations with a common statistical period of 50 years (1969-2019) were selected. The results showed that the trend of drought in winter and summer is increasing in all studied climates. The highest correlation (0.80-0.99) between SPI-RDI and SPEI-RDI indices in coastal desert, mountain and semi mountain climates and the lowest correlation (0.34) between SPI-SPEI and SPEI-RDI indices in semi desert, desert and coastal desert climates were obtained. The comparison of the results in the trend analysis of the drought showed the same trend, but the SPEI index compared to the other indicators showed a quicker response to changes in drier climates. SPI-RDI variations showed similar values in colder climates. The SPEI is based on precipitation and temperature data, and it has the advantage of combining multi-scalar character with the capacity to include the effects of temperature variability in the drought assessment. Thus, SPEI is recommended as a suitable index for studying and identifying the effect of climate change on drought conditions.

Key words: Climate classification, Drought severity, Reference evapotranspiration, Season

1. Introduction

Today, many countries are experiencing the negative effects of global warming and climate change (Bachmair et al., 2016; Mazdiyasnand & AghaKouchak, 2015; Huang et al., 2016; Ficklin et al., 2015). Drought and water scarcity can cause serious crises in human social life, such as the competition over access to water resources, endangering public health, and adverse environmental and ecological impacts (Hosseini-Moghari & Araghinejad, 2015; Haile et al., 2019). Therefore, considering the climatic conditions, especially in arid and semi-arid regions, the study of drought status can be an important role in providing forecasting to achieve the stability of systems (Sharafi et al., 2016). Since drought is a natural and recurring phenomenon that occurs due to reduced rainfall over a specified and relatively long period of time (Sharma & Mujumdar, 2017), one of the important components of drought planning is the provision of timely and reliable climate

information, including seasonal forecasts, which assist decision makers at all levels in managerial decisions. This information, if used properly, is crucial to understanding the effects of drought on various components of the hydrological cycle.

However, with rising temperatures and, consequently, increased reference evapotranspiration (ET_{ref}), declining precipitation and severe climate change are putting more pressure on water resources and agriculture; therefore, decision makers must have accurate information about the amount of evapotranspiration and drought risk assessment for each region (Byakatonda et al., 2018; Vicente-Serrano et al., 2014; Wang et al., 2012). Assessing drought caused by climate change using long-term meteorological data can be effective in predicting climate change (Guo et al., 2017), but with the complexity of the drought, it is much more difficult to quantify. Lack of direct methods for drought assessment has led to the use of drought indicators that proxy the effects of drought on hydrological systems (Svoboda et al., 2016; Byakatonda et al., 2018; Yihdego et al., 2019). The first step is the selection of climatic parameters affecting the accurate assessment of ET_{ref} and its effect on the accurate assessment of drought indicators. For example, it is not yet clear whether an increase in temperature automatically translates into an increase in ET_{ref} demand, as one theory holds that other meteorological variables such as wind speed, relative humidity, and sunshine hours may not vary with temperature (McEvoy et al., 2012; Vicente-Serrano et al., 2015). However, so far more than 50 methods of estimating ET_{ref} have been presented in the form of combined methods, aerodynamic and empirical, which often have different results according to meteorological data (Sharafi & Mohammadi Ghaleni, 2021). In addition, the accuracy and sensitivity of the ET_{ref} equation is very important, which can even provide important evidence for identifying models that have a more accurate estimate of drought under climate change conditions. For example, complex models such as the Penman-Monteith equation based on FAO 56 (PM-FAO_{56}) is often recommended because of its ability to better represent climatic variables that affect ET_{ref} (Lu et al., 2016). To calculate accurately the PM-FAO_{56} equation, required climatic variables include maximum, minimum and average temperatures, precipitation, relative humidity, wind speed and solar radiation (Kisi et al., 2015).

Among the various drought indices, the SPI has been studied worldwide (Güner Bacanli 2017; Pathak & Dodamani, 2019). However, since SPI does not consider the effect of meteorological variables (maximum and minimum temperature, relative humidity and ET_{ref}) in the accurate assessment of drought. For this purpose, Vicente-Serrano et al. (2010) proposed SPEI and RDI, respectively (Vicente-Serrano et al. 2015; Mohammed & Scholz, 2017). In addition to precipitation, the effect of ET_{ref} is also measured in SPEI and RDI indices (Vicente-Serrano et al. 2010b). Therefore, it is necessary to use various drought indicators to identify climatic regions with similar drought behavior (Dai 2011; Pathak & Dodamani, 2019).

Numerous studies have been conducted on the evaluation of SPI, SPEI and RDI drought indices in different climates (Cloppet, 2011; Yihdego et al., 2019; Pathak & Dodamani, 2019; Mehr & Vaheddoost, 2020). However, the results of no one of them have been accepted worldwide, because other factors such as land use, vegetation, human factors, biodiversity, etc. also have a significant impact (Mohammed & Scholz, 2019; Yihdego et al., 2019; Wable et al., 2019; Jehanzaib et al., 2020; Wang et al., 2020; Salimi et al., 2021). Mahmoudi et al. (2019) compared the performance of seven precipitation-based drought indices and found SPI the best index for drought monitoring in Iran. Liu et al. (2017) found that estimating trends in SPI for various timescales is inadequate for accepting the variations in droughts or determining the impact of climate change on the frequency and intensity of droughts. Therefore, it is essential to evaluate the variations in spatial levels of different drought features. Tsakiris et al. (2007) in their study

compared SPI and RDI indices in the Mediterranean climate. To evaluate the performance of the RDI index, they used its correlation with the SPI index and stated that RDI has a high behavioral similarity with SPI. Potop & Možný (2011) examined the application of the SPEI index as a new drought index in the Czech Republic and concluded that regardless of the time scale, this index has the ability to detect the severity of drought under the influence of increasing temperature conditions. Their results also showed that the assessment of drought over ten-year periods was due to the increase in ET_{ref}. According to the mentioned cases, it seems that different indicators of meteorological drought monitoring in different climates do not always show the same behavior in monitoring the meteorological drought situation. Also, in two separate studies on the comparative evaluation of SPI with RDI that identified different climate conditions, RDI was recommended in the drought monitoring systems of Iran (Jamshidi et al. 2011; Zarch et al. 2011). Also, Vicente-Serrano et al. (2015) and Salimi et al. (2021) reported that the SPEI in caparison with SPI, had better capability in representing drought situation.

Iran is located in the arid and semiarid zones of the world. Also, according to the present authors' best knowledge, no studies have focused on examining the ET_{ref}-based drought indices exclusively at the climate and season levels. The current study aims to compare the multivariate meteorological drought indices for Iran's climate by considering the four seasons that consist of six major climatic regions of the country. Therefore, the study includes the following objectives: 1) Investigation of trends associated with the meteorological variables (Tmin. Tmax, precipitation and ET_{ref}); 2) Assessment of drought characteristics, estimated from SPI, RDI, and SPEI and its spatiotemporal variation at various time scales and 3) Comparison of these drought indices in different climatic regions and various seasons within the study area.

2. Materials and Methods

2.1. Time and location scales

Iran, with area 1.65 million km^2, is located at longitude 25–40 °N and latitude 44–65 °E and over of the country, involved with desert and semi desert climates. The highest elevations are found in the Zagros and Alborz mountain ranges, which block moisture from the mountain, semi mountain (northwest and west) and coastal wet (north) climates, resulting in uneven distributions of temperature and precipitation across the country (Fig. 1). Therefore, in order to evaluate the hydrological drought indices, 50 years of long-term meteorological data were gathered from 43 synoptic stations (1969-2019). These stations formed almost all the important geographical areas of the country. Climatic data included values of maximum temperature (T_{max}), minimum temperature (T_{min}), average temperature (T_{mean}), relative humidity, dew point temperature, precipitation, sunshine hours, cloudy days and solar radiation. Observations that were suspicious or incorrect were removed from the list. The month and day formats were replaced by the day format of the year (DOY). The stations studied based on climatic classification of Alijani et al. (2008) in 6 climatic zones included wet coastal, mountain, semi mountain, semi desert, desert and coastal desert. Fig. 1 shows the geographical location and climatic classification based on the values of T_{min}, T_{max}, precipitation and ET_{ref} for the four seasons at the studied stations.

2.2. Data analysis

First, initial statistical tests were performed on meteorological data. For this purpose, the Mann-Kendall test was used to detect the trend and Grabs-Back test was used to find data. In the meantime, missing data such as temperature, sunshine and relative humidity were restored through

FAO guidelines and precipitation and wind speed parameters through average ratios. The PM-FAO_{56} empirical equation was used for ET_{ref} calculations (Sharafi & Ghalenee, 2021).

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

In these equations, for ET_{ref}, these variables are used: reference evapotranspiration (mm month^{-1}), Δ; the slope of the saturation vapor pressure function (kPa $^{\circ}$C), R_n; net radiation (MJ m^{-2} d^{-1}), G; soil heat flux density (MJ m^{-2} d^{-1}), γ; psychometric constant (kPa $^{\circ}$C), T_a; average air temperature ($^{\circ}$C), u_2; average wind speed at 2 m height (m s^{-1}), e_s; saturation vapor pressure (kPa) and e_a; actual vapor pressure.

The T_{mean}, T_{min} and T_{max} over Iran and the whole study period 1969–2019 are 18.3, 11.5 and 25.1°C respectively. Mean annual precipitation and ET_{ref} in the same period is 393 and 759 mm. In 67% of the country, mean annual precipitation is less than 156 mm (Fig. 1). The spatial differences of 16.65°C for mean temperature and 1107 mm per year for precipitation show the climate diversity in Iran, as also reported in previous researches (Madani, 2014; Panahi et al., 2020).

Based on T_{min}, T_{max}, P and ET_{ref} values, Babolsar, Bandar Anzali, Ramsar, Rasht and Gorgan were stations in coastal wet climate; Khoy, Nozheh, Sanandaj, Saqez, Tabriz, Urmia and Zanjan stations in mountain climate; Arak, Dezful, Kermanshah, Khorramabad, Qazvin and Shahrekord stations in semi mountain climate; stations of Birjand, Fasa, Isfahan, Kashan, Mashhad Sabzevar, Semnan, Shahroud, Shiraz, Tehran and Torbat Heydarieh in semi desert climate; Bam, Kerman, Iranshahr, Tabas, Yazd, Zabol and Zahedan stations in desert climate and the stations of Abadan, Ahvaz, Bandar Abbas, Bandar Lengeh, Bushehr, Chabahar and Jask were located in coastal desert climate (Fig. 1).

Annual average T_{min} varied from -1.5 to 21.8 (≈7.1°C) in autumn season, -6.4 to 18.4 (≈3.1°C) in winter season, 6.4 to 26.8 (≈15.6°C) in spring season and 10.9 to 30 (≈20.2°C) in summer season. Annual average T_{max} varied from 12.3 to 33.3 (≈20.3°C) in autumn season 6.3 to 27.2 (≈14.8°C) in winter season, 21.6 to 44.5 (≈30°C) in spring season and 28.1 to 48.7 (≈35.5°C) in summer season. Furthermore, in desert and coastal desert climates, there is no significant difference between the T_{min} and T_{max} in spring and summer seasons (Fig. 1). These recordings have about the same gradient. The valleys in the mountain are normally colder in winter compared to the foothills. However, summers in these foothills are normally warmer.

Annual precipitation declines from > 1162, 385 and 340 mm (coastal wet, semi mountain and mountain climates, respectively) to < 216, 170 and 83 mm (semi desert, coastal desert and desert climates, respectively). These recordings have about the same gradient in autumn, winter and spring seasons. Also, annual ET_{ref} increased from > 3469, 3383 and 2327 mm (coastal desert, desert and semi desert climates, respectively) to < 1545, 1415 and 1048 mm (semi mountain, mountain coastal wet climates, respectively).

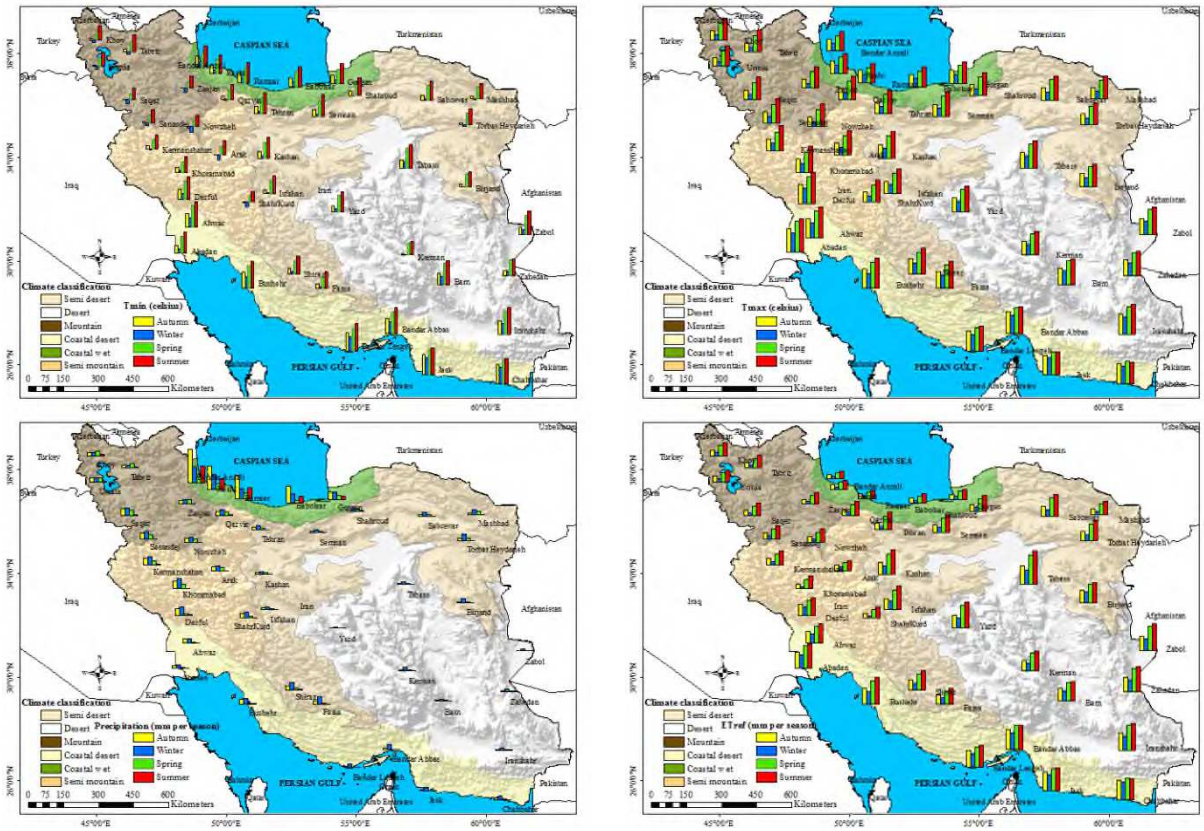


Fig. 1. Geographical situation and climate classification based on the values of T_{min}, T_{max}, precipitation and ET_{ref}

2.3. Mann-Kendall test

Table 1 shows the statistical values in the form of heating map and significance at the level of 1 and 5%. According to the Mann-Kendall test results, many stations show an increase in T_{min} and T_{max} during the fall, winter, spring and summer seasons. The slope of the warming trend was much steeper in winter and summer. In coastal wet and coastal desert climates, the trend of increasing T_{min} was observed during four seasons.

In general, during the last 50 years, in coastal wet, mountain, semi mountain, semi desert, desert and coastal desert climates, about 70, 65, 80, 77, 80 and 90% of precipitation, respectively, occurs in autumn and winter, respectively. Therefore, the study of this climatic parameter has a very important role in better assessment and understanding of drought indicators. Accordingly, in all studied climates, a trend of reduced precipitation was observed, especially in winter; however, in mountain and semi mountain climates, this declining trend was more severe. Also, a decrease in precipitation in spring season was observed for stations in coastal wet and mountain climates. On the other hand, in most semi mountain, desert and coastal desert climates, the amounts of increase in precipitation were reported in autumn season, although these values were not significant.

According to the results of preliminary studies, ET_{ref} values in most of the stations studied in different climates have an increasing trend, which had a positive and significant trend in winter and summer. The difference in ET_{ref} values in coastal wet and coastal desert climates is about 2400 mm per year. This amount of ET_{ref} in coastal desert climate is even higher than in desert climate, which is due to the high RH in this climate.

Table 1. The results of Mann-Kendall test for the studied stations

Class	Station	Tmin				Tmax				Precipitation				ET_{ref}			
		Aut.	Win.	Spr.	Sum.	Aut.	Win.	Spr.	Sum.	Aut.	Win.	Spr.	Sum.	Aut.	Win.	Spr.	Sum.
Coastal wet	Babolsar	Δ	▲	▲	▲	●	▲	●	▲	o	o	o	●	o	Δ	●	Δ
	Bandar Anzali	●	▲	Δ	▲	●	▲	●	●	o	∇	o	●	o	●	o	o
	Ramsar	Δ	▲	▲	▲	●	▲	●	▲	●	●	o	●	o	▲	●	Δ
	Rasht	Δ	▲	Δ	▲	●	Δ	●	●	o	o	o	●	o	●	●	●
	Gorgan	o	●	●	●	o	▲	Δ	▲	∇	o	▼	o	●	▲	▲	▲
Mountain	Khoy	●	▲	▲	▲	●	▲	Δ	▲	o	▼	o	●	●	▲	Δ	▲
	Nowzheh	Δ	▲	●	▲	●	▲	●	●	●	▼	o	●	●	▲	●	Δ
	Sanandej	●	▲	▲	▲	●	▲	●	▲	●	▼	o	Δ	●	▲	Δ	▲
	Saqez	●	●	▼	o	o	Δ	●	o	●	▼	∇	●	o	Δ	●	o
	Tabriz	●	▲	●	▲	●	▲	Δ	▲	o	▼	∇	●	●	▲	Δ	▲
	Urmia	●	▲	●	●	●	▲	Δ	▲	●	●	o	●	●	▲	Δ	▲
	Zanjan	●	▲	●	●	●	▲	●	Δ	●	o	o	Δ	●	▲	●	Δ
Semi mountain	Arak	▲	▲	▲	▲	▼	▼	▼	▼	o	▼	●	●	o	Δ	●	●
	Dezful	▼	▼	o	o	▲	▲	▲	▲	●	▼	o	Δ	▲	▲	▲	▲
	Kermanshah	Δ	▲	▲	▲	●	▲	Δ	▲	●	∇	o	●	●	▲	Δ	▲
	Khoramabad	o	●	●	●	o	●	●	▲	●	∇	●	●	o	●	●	▲
	Qazvin	●	▲	●	Δ	●	▲	●	●	●	o	o	●	●	▲	●	●
	Shahrekord	o	●	▼	▼	o	▲	●	o	●	o	●	Δ	o	Δ	o	▼
Semi desert	Birjand	●	●	●	●	o	Δ	●	●	●	o	●	●	●	Δ	●	●
	Fassa	▲	▲	▲	▲	▼	▼	▼	▼	o	o	o	●	▼	▼	▼	▼
	Isfahan	●	●	●	●	●	▲	●	▲	o	o	●	●	●	Δ	●	●
	Kashan	●	Δ	●	●	o	●	●	o	●	o	●	●	●	●	●	●
	Mashhad	▲	▲	▲	▲	●	▲	●	▲	●	o	●	▲	●	▲	Δ	▲
	Sabzevar	●	▲	●	Δ	●	▲	●	●	o	∇	●	●	●	▲	●	Δ
	Semnan	●	▲	Δ	Δ	o	●	●	●	●	o	●	●	o	●	●	●
	Shahroud	Δ	▲	▲	▲	●	Δ	●	●	o	o	∇	●	●	Δ	●	●
	Shiraz	●	Δ	Δ	▲	●	Δ	●	Δ	●	o	●	Δ	●	Δ	●	▲
	Tehran	●	▲	Δ	▲	●	▲	●	●	●	o	o	Δ	o	Δ	●	●
	Torbat Heydarieh	●	●	●	Δ	o	●	o	o	●	o	●	●	o	●	●	o
Desert	Bam	Δ	▲	▲	▲	●	Δ	●	▲	o	o	o	o	●	Δ	●	▲
	Kerman	▲	▲	●	Δ	●	▲	●	Δ	●	▼	o	●	Δ	▲	●	Δ
	Iranshahr	Δ	Δ	Δ	▲	o	●	o	●	●	o	●	●	●	●	●	●
	Tabass	▲	▲	▲	▲	●	●	●	●	●	●	●	●	●	▲	▲	▲
	Yazd	▲	▲	▲	▲	●	▲	●	●	●	∇	●	Δ	●	▲	Δ	▲
	Zabol	●	●	●	▲	●	▲	●	▲	●	o	●	o	●	Δ	●	▲
	Zahedan	●	Δ	▲	Δ	●	▲	●	●	●	o	●	Δ	●	▲	●	●
Coastal desert	Abadan	●	▲	▲	▲	●	Δ	▲	▲	●	▼	●	o	●	Δ	▲	▲
	Ahwaz	▲	▲	▲	▲	●	Δ	●	▲	o	∇	o	o	o	●	o	▼
	Bandar Abbas	▲	▲	▲	▲	▼	▼	▼	▼	Δ	o	●	●	▼	▼	▼	▼
	Bandar Lengeh	▲	▲	▲	▲	●	▲	●	▲	●	o	●	●	●	Δ	●	▲
	Bushehr	▲	▲	▲	▲	o	●	▼	▼	●	o	●	▲	●	Δ	▼	▼
	Chabahar	▲	▲	▲	▲	o	o	∇	▼	o	o	o	o	∇	o	▼	▼
	Jask	▲	▲	▲	▲	●	Δ	●	o	●	▼	Δ	o	▲	▲	Δ	Δ

▲; significant at 1% with positive trend, ▼; significant at 1% with negative trend, Δ; significant at 5% with positive trend, ∇ ; significant at 5% with negative trend, ●; not significant with positive trend and o; not significant with negative trend.

$\tau \leq -0.2$	$-0.2 < \tau < -0.05$	$-0.05 \leq \tau \leq 0.05$	$0.05 < \tau < 0.2$	$\tau \geq 0.2$

2.4. Determine the changing point (CP) using Pettit's test

Time of significant change in time series (changing point) is of particular importance in describing their behavior. In order to detect the CP in time series, several methods are used. In this paper, the non-parametric test proposed by Pettit (1979) was used. This test determines the time of occurrence of significant changes in the mean of the time series. The test statistic is $\mu_{t,N}$, which confirms whether the two sample sets $X_1,\ldots, X_t$ and $X_{t+1} \ldots\ldots X_N$ are from the same statistical population, and is defined as Eq. 2 (Gao et al., 2012):

$$\mu_{t,N} = \mu_{t+1} + \Sigma_{j=1}^{N} \operatorname{sgn}(X_t - X_i) \quad for\, t = 2,\ldots, N \tag{2}$$

Where N; total number of observations, X_t; the first set and X_j; is the second set. The K_N test statistics and the associated probability of occurrence are calculated by Eqs. 3 and 4:

$$K_N = \max 1 \leq t \leq N \left|\mu_{t,N}\right| \tag{3}$$

$$P\ ;\ 2\exp\left\{-6\frac{(K_N^2)}{(N^3+N^2)}\right\} \quad (4)$$

In the next stage, the drought situation in the monthly period was determined based on SPI, RDI and SPEI indicators in each station and based on each of the indicators. In this study, the drought situation was examined on an annual scale in 12 consecutive months ending in September of each year, because in terms of agriculture and water resources, each crop year or water year is in this period. On the other hand, on an annual scale, the effect of seasonal fluctuations in precipitation and relative humidity is somewhat combined, so the drought (humidity) in each season was evaluated independently of other seasons in this study, which this is also a special case on a quarterly scale. In terms of agriculture and water resources, the study of seasonal fluctuations in rainfall and drought is also very important (Sharafi et al., 2016).

2.5. Drought indicators

2.5.1. SPI index

The SPI index was developed by McKee et al. (1993) to determine periods and severity of drought. SPI calculates precipitation deficit at different time scales (Yihdego et al., 2019). This index is calculated for each climate based on the recording of long-term precipitation. In this method, first, the appropriate statistical distribution is fitted to the long-term precipitation statistics, then, the cumulative distribution function is converted to a normal distribution using equal probabilities, so that in the period under review, the average standardized precipitation values equal zero and deviate from their standard by one (Edwards and McKee, 1997). To fit the precipitation data, the gamma distribution is the most accurate distribution. In some climates, however, the gamma distribution may be fitted as the most appropriate distribution for precipitation data (Logan et al., 2010). In fact, SPI is a variable of the standardized normal distribution function whose cumulative probability value is equal to the cumulative probability value of the variable obtained from the obtained gamma distribution (Svoboda et al., 2016).

2.5.2. RDI index

This index was first introduced by Tsakiris and Vangelis (2005). In order to calculate the normal log distribution function on the cumulative values, the ratio of precipitation to ET_{ref} is fitted and then the obtained values are standardized (Tsakiris et al., 2007). In this regard, first, using the values of precipitation ratio to ET_{ref}, the initial values for each time period are calculated according to Eq. 5:

$$a_k = \frac{\sum_{i=1}^{i=k} P_i}{\sum_{i=1}^{i=k} ET_{ref-i}} \quad (5)$$

Where P_i and $ET_{ref\text{-}i}$ are the reference values of precipitation and evapotranspiration of the i^{th} month, respectively. Normalized RDI values (RDI_n) are calculated according to Eq. 6 using the values calculated for different years in the previous equation.

$$RDI_{n(k)} = \frac{a_k}{\overline{a}_k} \quad (6)$$

Where $\overline{a}_k$ is the arithmetic mean of the values in the years under review. To calculate the standardized RDI (RDI_{st}), it is assumed that the $\overline{a}_k$ values follow the normal log distribution. $\overline{a}_k$ values for different years are calculated using Eq. 7:

$$RDI_{n(k)} = \frac{Y_k - \overline{Y}_k}{\hat{\sigma}_k} \quad (7)$$

Where Y_k is equal to $\ln a_k$, $\overline{Y}$, and $\hat{\sigma}$ are the arithmetic mean and standard deviation of the values of Y_k, respectively. Thus, the RDI is calculated in three steps, which include initial values, normalized values, and standardized values. Standardized values can be compared with SPI (Hatefi et al., 2016; Yihdego et al., 2019).

2.5.3. SPEI index

SPEI by Vicente-Serrano et al. (2010a) was proposed as an indicator of drought, which is particularly appropriate for studies of the effect of global warming on the severity of drought. This index also determines the effect of ET_{ref} on drought severity and the nature of the Multi Scalar SPEI index (precipitation variable and other variables affecting ET_{ref}) and helps to determine the type of drought and its effects on different systems (Vicente-Serrano et al., 2012; 2013). Another advantage of the SPEI index over other drought monitoring indices is that it has the ability to detect the effect of changes in ET_{ref} values and temperature in relation to global warming (Svoboda et al., 2016; Byakatonda et al., 2018). Beguer´ıa et al. (2014) provided a complete description of the logic governing SPEI and how to calculate it and compare it with other drought assessment indices. The method of calculating SPEI is similar to SPI. In addition, the SPEI seems to provide a more accurate index of drought severity than just precipitation because of the difference between precipitation and ET_{ref}. To calculate the SPEI index, first the amount of ET_{ref} for each month was estimated, and then through a simple water balance model, the difference between the amount of precipitation and the amount of ET_{ref} for the first month of Eq. 8 was calculated.

$$D_i = P_i - ET_{\mathrm{Re}f-i} \quad (8)$$

Calculating this index, like the method presented for calculating the SPI index, requires estimating the cumulative probability values of D_i values by fitting a probability density function. Since the values of D_i lead to negative values from the lower bound, the two-parameter probability functions cannot be selected for this value. Vicente-Serrano et al. (2010a), by examining different three-parameter functions, identified the three-parameter log-logistic probability density function as having the best fit for D_i values. The general form of the probability density function of this function is shown in Eq. 9:

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}\left[1+\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right]^{-2} \quad (9)$$

Where the parameters α, β and γ are the scale, shape and principal parameters for the values of D_i in the domain $\gamma \geq D \leq \infty$, respectively. The form of the three-parameter log-logistic cumulative probability function is also calculated according to Eq. 10:

$$f(x) = \left[1+\left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1} \quad (10)$$

Finally, the cumulative probability values for the cumulative probability values for the D_i values are converted to a standardized normal function with a mean of zero and a standard deviation of one equal to the SPI values. The classical Abramowitz and Stegun function (1965) is an estimate of the SPEI value using the values of the function F(x) (Eq. 11):

$$SEPI = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W + d_3 W^3} \quad (11)$$

The values of W for different time periods are calculated from Eq. 12:

$$W = \sqrt{-2\ln(P)} \rightarrow P \leq 0.5 \quad (12)$$

Where P is the probability value in excess of the set value D (P=1-F(x)). If the value of P is greater than 0.5, the P value is replaced by 1-P and the SPEI result symbol is replaced. The value of constant coefficients in Eq. 8 is equal to:

C_0= 2.515517 d_0= 1.432788
C_1= 0.802853 d_1= 0.189269
C_2= 0.010328 d_2= 0.001308

2.6. Drought category

SPI concepts have been used in the development of RDI and SPEI indices. Thus, the values of the different classes of drought severity in them are similar to those presented by SPI, as shown in Table 2 (Edwards and McKee, 1997). According to this method, the drought period occurs when the SPI is continuously negative and reaches a value of -1 or less and ends when the SPI value becomes positive.

Table 2. Different categories of drought conditions according to SPI, RDI and SPEI indices

Drought class	Symbol	Index value
Extremely wet	EW	2 or more
Severely wet	VW	1.5 to 1.99
Moderately Wet	MW	1 to 1.49
Normal	N	0.99 to -0.99
Moderately Drought	MD	-1 to -1.49
Severely Drought	SD	-1.5 to -1.99
Extremely Drought	ED	-2 or less

3. Results and discussion

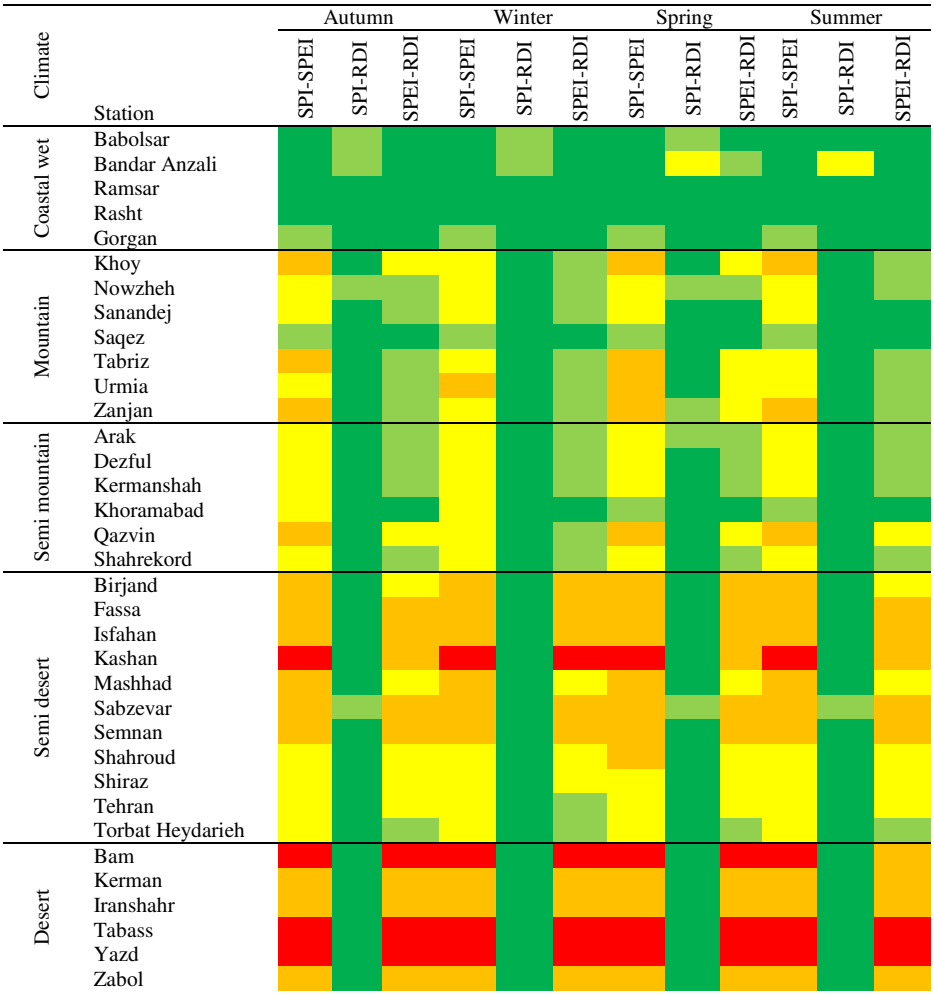
3.1. Correlation analysis

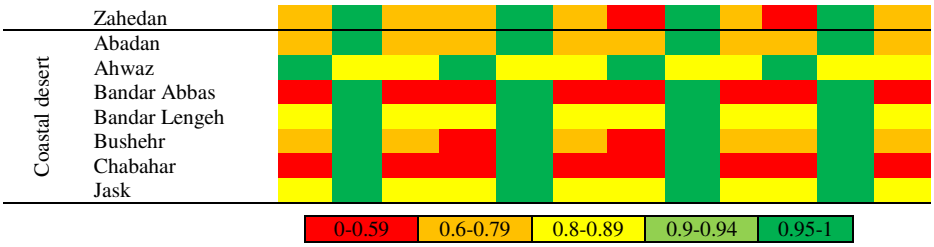
Based on the results of the Pearson correlation coefficient, the highest correlation was observed between SPI and RDI during four seasons: autumn, winter, spring and summer (R=0.95-1). On the other hand, the lowest correlation coefficient between SPI and SPEI was observed in desert climates and semi desert in quadruple climates ($R \leq 0.79$). By moving from a wetter climate (such as coastal wet and mountain) to a drier climate (such as desert and coastal desert), the correlation between the SPI and SPEI, SPEI and RDI indices has been greatly reduced. Due to the direct effect of T_{min} and T_{max} in the evaluation of SPEI and RDI indices, the difference between T_{min} and T_{max} should be evaluated. Accordingly, in humid (such as coastal wet) and very dry climates (such as semi desert, desert and coastal desert), the difference between T_{min} and T_{max} in winter (cold season) and summer (warm season) was reported 1 and 2-3 degrees Celsius, respectively. However, the

difference between T_{min} and T_{max} between cold and hot seasons in mountain and semi mountain climates was between 11 to 18 and 13 to 20 $^{\circ}$C (Fig. 2).

The Pearson correlation matrix shows that the SPI drought index is better than the SPEI drought index in wet climates (Salimi et al., 2021). Also, they reported that wet climates have less ET_{ref}. It means that the drought indices in the humid climates affect the hydrological drought at drier seasons and the maximum correlation is observed for wet seasons. Furthermore, there are seasonal variations in cross-correlation coefficients, which can be explained by the fact that metrological drought indices in response to the deficit in precipitation may differ significantly, depending on seasonal variations. Additionally, it can be concluded that a stronger relationship begins when precipitation starts after a long, dry summer season in Iran. In this stage, the water moves both through the soil and over the surface via a range of hydrologic processes such as infiltration and runoff throughout the autumn and winter. Simultaneously, it appears that during a dry season (summer) there is a more robust relationship between the SPI and RDI. It can be concluded that the SPEI has a delayed response to the SPI during the dry season, whereas in coastal wet climate, the prompt response of the SPEI and RDI to the SPI is dominant. In this perspective, it is acknowledged that the characteristics of the meteorological drought, too, are significantly dependent on the seasonal variations.

Fig. 2. Heat map for showing cross-correlation coefficients between SPI, SPEI and RDI in different climates and seasons of Iran





3.2. CP analysis

Drought characteristics were extracted from SPI, SPEI and RDI time series from different climates and seasons. This provides a comprehensive view of meteorological droughts at the national scale, that have been relatively under-used in Iran. Table 3 shows the trend of significance, the CP of drought, the first mutation and the second mutation in six climates and in four seasons. Based on P-value results, SPI, SPEI and RDI indices were significant in all climates and seasons studied (60% ≤ coverage < 80% among all stations in each climate). This confirms that according to the results of the studied indices, during the past half century, drought was found in all climates and seasons of Iran. Also, according to the results of Table 3, the CP was reported to be decreasing in almost all climates and seasons. For example, the CP in the coastal wet climate began in November 1988. CP has been observed in mountain, semi mountain and coastal desert climates since November 1998 and was the same in almost all seasons). This shows that the changes in these climates were due to the human effects of previous years. Factors such as the destruction of forests and pastures (conversion to agricultural fields, especially in mountain and semi mountain climates) and the uncontrolled construction of dams in this period and in the years before the occurrence of successive droughts have had a direct impact on the occurrence and registration of droughts. Furthermore, based on the research of Tabari et al. (2013), almost all climates experienced extreme droughts in Iran. The changing point of drought events occurred mainly from 1998–2009 and the hydrological years of 1998–1999, 1999–2000 and 2000–2001 were the driest years during the studied period.

Table 3. Significant trend based on Pettit's test in drought indices in different climates and seasons of Iran

		SPI				SPEI				RDI			
Climate	Season	CP	P-value	μ_1	μ_2	CP	P-value	μ_1	μ_2	CP	P-value	μ_1	μ_2
Coastal wet	Aut.	Nov-88	0.0001	0.265	-0.272	Nov-88	0.005	0.217	-0.324	Nov-88	0.002	0.217	-0.329
	Win.	Feb-89	0.048	0.171	0.04	Feb-89	0.244	0.225	-0.336	Feb-89	0.355	0.222	-0.338
	Spr.	May-89	0.013	0.163	-0.006	May-89	0.075	0.235	-0.346	May-89	0.0001	0.22	-0.344
	Sum.	Jul-14	0.006	0.276	-0.264	Jul-14	0.002	0.298	-0.277	Jul-14	0.001	0.222	-0.313
Mountain	Aut.	Nov-98	0.0001	0.343	-0.414	Nov-98	0.0001	0.495	-0.601	Nov-98	0.0001	0.439	-0.355
	Win.	Feb-98	0.0001	0.344	-0.44	Feb-98	0.0001	0.516	-0.587	Feb-98	0.0001	0.421	-0.441
	Spr.	May-98	0.0001	0.38	-0.411	May-98	0.0001	0.53	-0.619	May-98	0.0001	0.48	-0.457
	Sum.	Aug-98	0.0001	0.365	-0.39	Aug-98	0.0001	0.523	-0.594	Aug-98	0.0001	0.47	-0.451
Semi mountain	Aut.	Oct-98	0.02	0.235	-0.451	Oct-98	0.0001	0.31	-0.529	Nov-96	0.000	0.281	-0.551
	Win.	Feb-98	0.005	0.254	-0.449	Feb-98	0.0001	0.334	-0.514	Feb-98	0.0001	0.286	-0.556
	Spr.	May-98	0.011	0.26	-0.473	May-98	0.0001	0.321	-0.523	May-98	0.0001	0.295	-0.554
	Sum.	Aug-98	0.002	0.237	-0.447	Aug-96	0.0001	0.378	-0.66	Aug-96	0.0001	0.283	-0.552
Semi desert	Aut.	Nov-99	0.044	0.099	-0.548	Nov-96	0.0026	0.308	-0.422	Nov-99	0.002	0.161	-0.518
	Win.	Feb-08	0.006	0.116	-0.502	Feb-98	0.0001	0.283	-0.444	Feb-08	0.03	0.152	-0.538
	Spr.	May-99	0.047	0.153	-0.474	May-98	0.0001	0.31	-0.477	May-07	0.001	0.2	-0.511
	Sum.	Aug-07	0.02	0.139	-0.48	Aug-96	0.0001	0.321	-0.442	Aug-07	0.001	0.182	-0.519
Semi desert	Aut.	Nov-99	0.0001	0.17	-0.468	Sep-98	0.0001	0.615	-0.823	Nov-98	0.001	0.197	-0.519
	Win.	Jan-00	0.0001	0.205	-0.457	Feb-99	0.0001	0.61	-0.814	Jan-00	0.025	0.254	-0.488

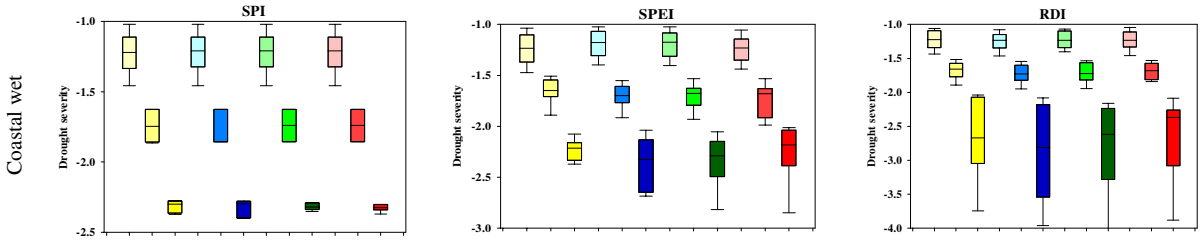
	Spr.	May-99	0.0001	0.186	-0.448	May-99	0.0001	0.645	-0.832	May-99	0.001	0.205	-0.521
	Sum.	Aug-99	0.001	0.175	-0.444	Aug-98	0.0001	0.641	-0.811	Aug-98	0.003	0.205	-0.506
Coastal desert	Aut.	Nov-98	0.0001	0.22	-0.515	Nov-98	0.0001	-0.079	-0.101	Des-98	0.0032	0.221	-0.525
	Win.	Des-98	0.001	0.21	-0.485	Feb-98	0.0001	-0.104	-0.048	Feb-98	0.003	0.22	-0.511
	Spr.	May-98	0.0001	0.236	-0.496	May-98	0.0001	-0.054	-0.274	May-98	0.0001	0.244	-0.522
	Sum.	Aug-98	0.0001	0.557	-0.49	Aug-98	0.0001	0.186	-0.672	Aug-98	0.005	0.241	-0.518

CP, changing point; μ_1, mutation 1; μ_2, mutation 2.
Positive and negative values indicate increasing and decreasing trends, respectively (60% ≤ coverage < 80%).

3.3. Drought severity

For each season in different climates, drought severity and the total number of events were identified using thresholds of -1 to -1.5, -1.5 to -2 and more than -2 (moderate, severe and extreme drought, respectively). For SPI and SPEI, more drought severity and the total number of events were identified at thresholds of more than -2. Spatial patterns for the maximum severity characteristic were similar for all three thresholds, and the results not be shown. The results for the thresholds of -1 to -1.5, -1.5 to -2 and more than -2 for different climates and seasons can be found in Figs. 3-6.

In general, the results showed that, for drought severity more than -2, there was comparatively little difference among different seasons (as shown by the clusters in Fig. 3), or around the country in the meteorological drought frequency extracted from SPI, SPEI and RDI time series (Fig. 4). While Iran has an order of magnitude precipitation gradient across the country, there is little difference in the severity and frequency of the meteorological drought indices. For SPI with increasing in drought severity, there is little variation between the four seasons' catchments, especially for the threshold of more than -2 in different climates (Fig. 3). This confirms that SPI index varies only modestly across the country over the threshold of more than -2 once the precipitation has been standardized. However, in SPEI and RDI index, these changes were much greater at low drought intensities (-1 to 1.5) and with increasing drought severity, the changes between seasons, especially at thresholds greater than 2, were more significant. In the SPEI index, changes in drought severity were greater in winter and spring for coastal wet, mountain and coastal desert climates. However, drought severity changes in autumn, spring and summer in semi mountain and semi desert climates were greater than in winter. Also, according to the results of the RDI index, the highest drought severity was observed in the thresholds higher than -2 in the four seasons. However, most of the changes in drought severity in winter were observed in coastal wet and mountain climates. Similarly, Barker (2016) found little spatial variation in the number and severity of meteorological events among catchments in the UK.



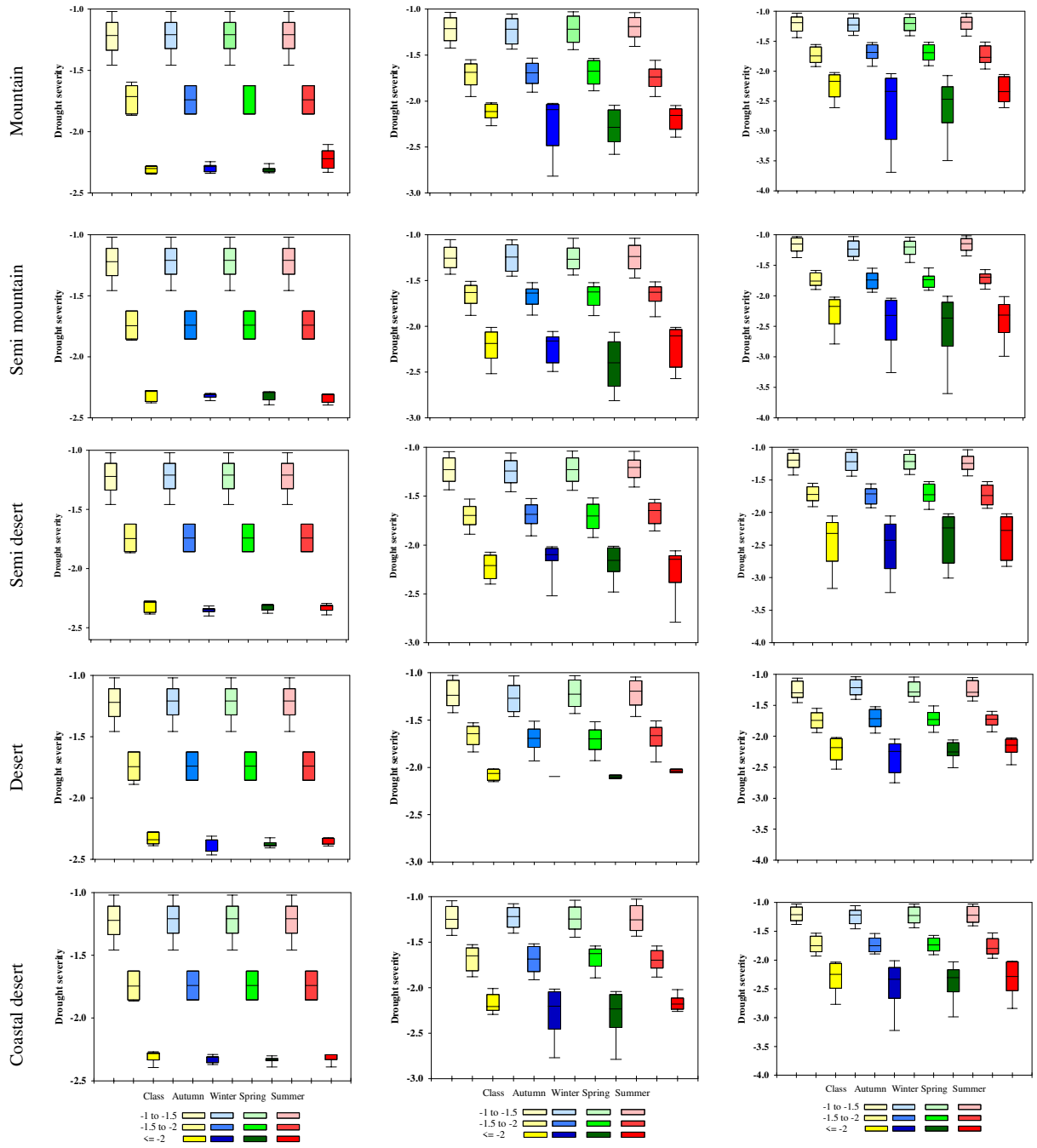


Fig. 3. Boxplots showing meteorological drought severity based on SPI, SPEI and RDI using thresholds of -1 to -1.5, -1.5 to -2 and ≤ -2 for each season

Fig. 4 shows the distribution of drought intensities at the threshold of -1 for the surveyed indices in four seasons. Table 1 shows that Iran has an order of negative precipitation gradient across the country (especially in winter season). Therefore, there is little difference in the median of drought severity. However, there may be differences in the results of drought indices in stations with similar climates. These differences in drought severity have also been found elsewhere, e.g. in coastal wet or coastal desert, where spatial variation was found to be the result of climatic variation across the mentioned climates. This result is confirmed by Panahi et al. (2020), who noted that the

coastal wet and mountain climates of Iran have more variability in drought severity and that the desert and coastal desert climates are subject to longer dry spells, so in practice these zones experience droughts in opposition.

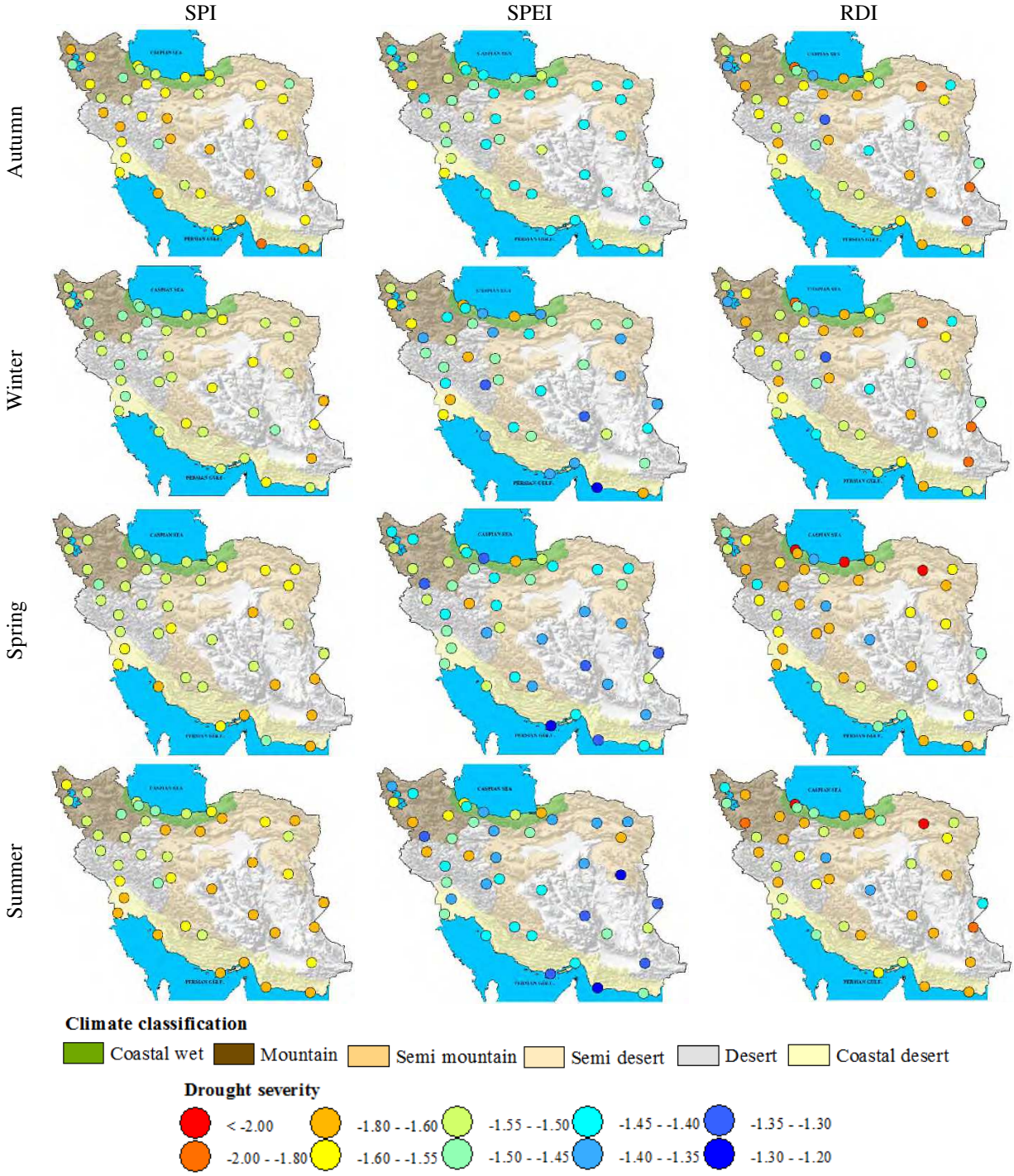
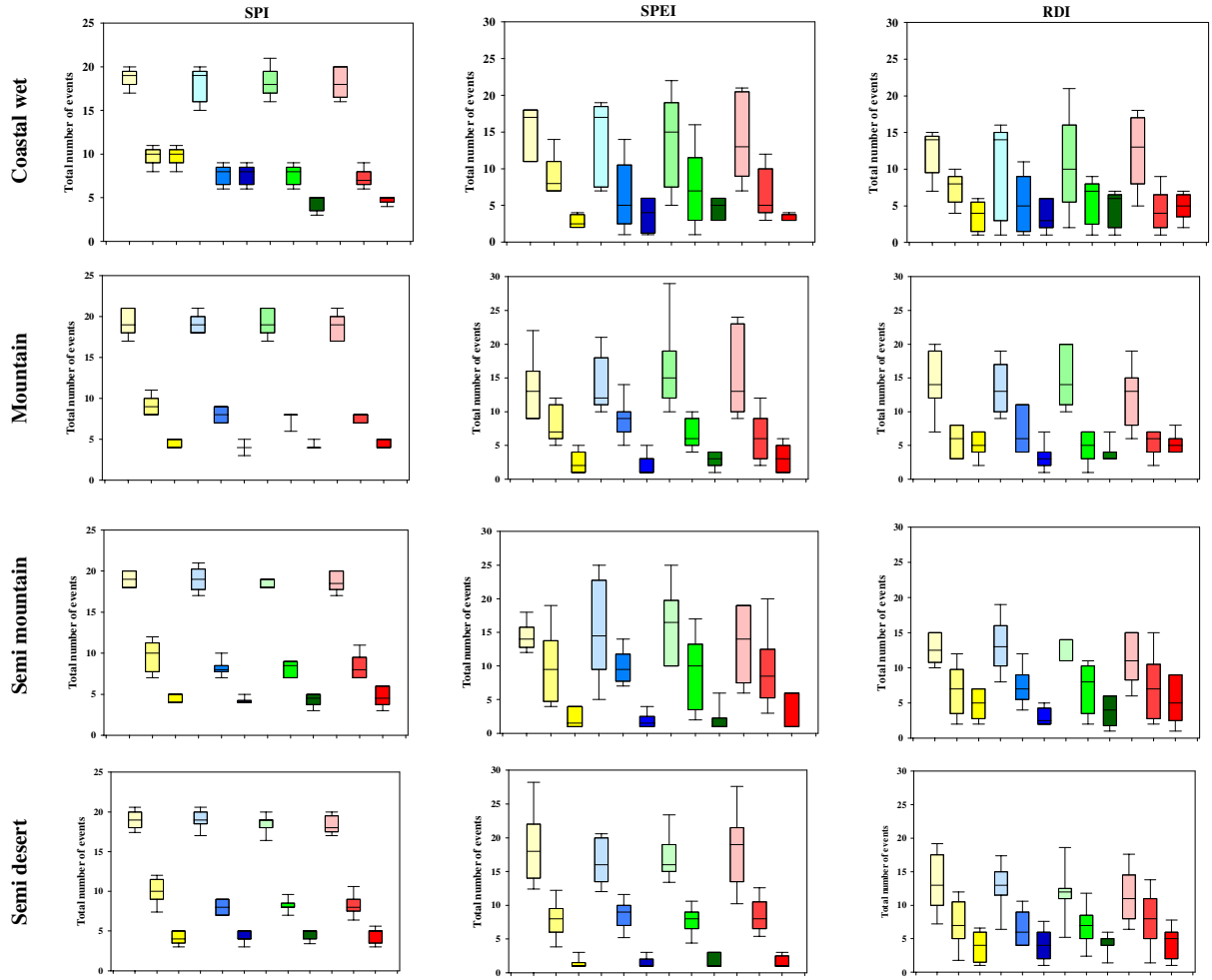


Fig. 4. Maps showing meteorological drought severity based on SPI, SPEI and RDI using a threshold of -1 for each season in Iran

3.4. Number of events

Compared to the SPI, the RDI shows fewer total events for both thresholds of -1.5 to -2 and more than -2, which can be attributed to the stronger persistence (i.e., a smaller fluctuation) that is more likely to be characterized by the SPI (Farahmand and AghaKouchak, 2015; Kwon et al., 2020). Furthermore, more frequent drought events appear to occur in thresholds of more than -2 for the SPI, SPEI and RDI indices (Fig. 5). It was also clearly seen that the total number of events for the SPEI is significantly longer than that of the SPI and RDI (especially in -1 to -1.5 threshold). On the other hand, SPI and RDI display negative values more frequently than does SPEI, and SPI recovers from wet states more quickly than does SPEI. More total events with the threshold -1 to -1.5 particularly stand out in coastal wet, mountain and semi mountain climates for SPI, while an increased frequency of moderate droughts is identified in all climates for SPEI and RDI indices.

In general, significant severe droughts in terms of both the total number of events and drought severity primarily occurred in all climates of Iran especially in wet seasons (autumn and winter). Also, the spatial distribution of drought characteristics associated with SPI is more dependent on the threshold, while SPEI and RDI are less sensitive to the threshold (Fig. 5).



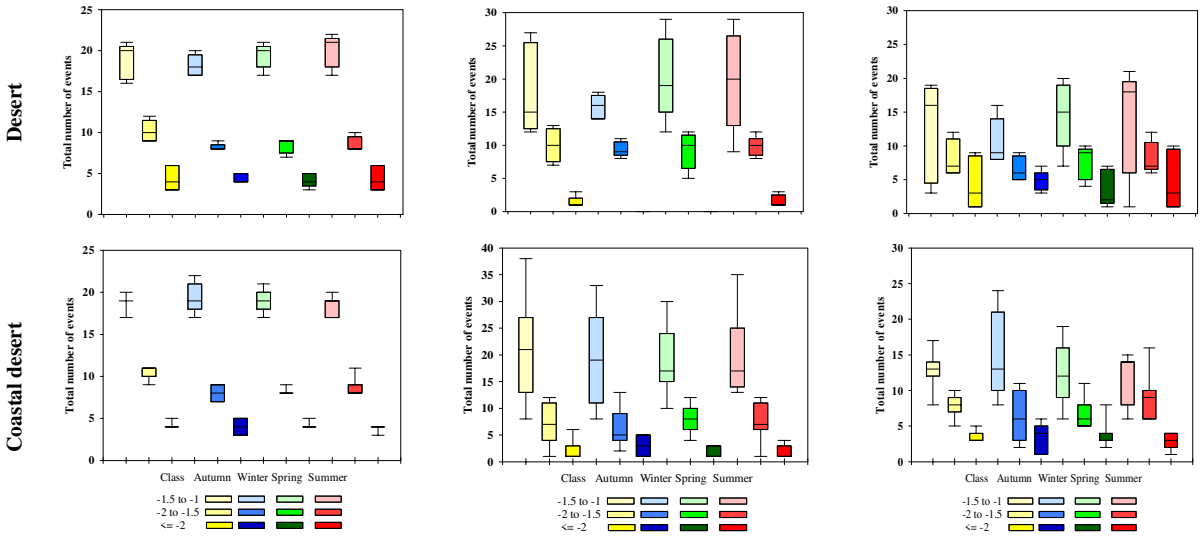
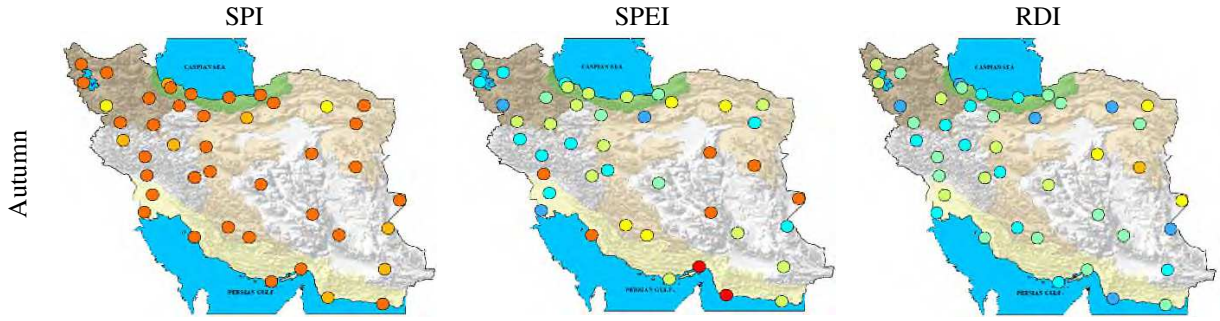


Fig. 5. Boxplots showing the total number of events based on SPI, SPEI and RDI using thresholds of -1 to -1.5, -1.5 to -2 and ≤ -2 for each season

Fig. 6 shows the total number of events detected by each of the drought indices in different climates and seasons in Iran. Accordingly, the highest number of events recorded by the SPI index was more than all other drought indicators in all climates and seasons. The number of drought events reported by the SPI index in all climates and seasons was greater than 30. This occurred while the highest record was detected by the SPEI in the autumn and winter seasons in coastal desert climate (e.g. Bandar Abbas station with 40 seasons).

In general, all three indices confirmed that in all climatic classes, the highest total number of recorded events occurred in the autumn season. However, on average, the number of drought events in the autumn for the SPI index was 19 and 32% higher than the SPEI and RDI indices, respectively. Also, the total number of drought events recorded in desert and coastal desert climates did not differ significantly in any of the seasons. However, these conditions were different for semi desert, semi mountain, mountain and coastal wet climates, so the total number of detected events in autumn and summer were more than in other seasons. This issue confirmed that the role of declining precipitation gradient in autumn is very disturbing (Fig. 6).



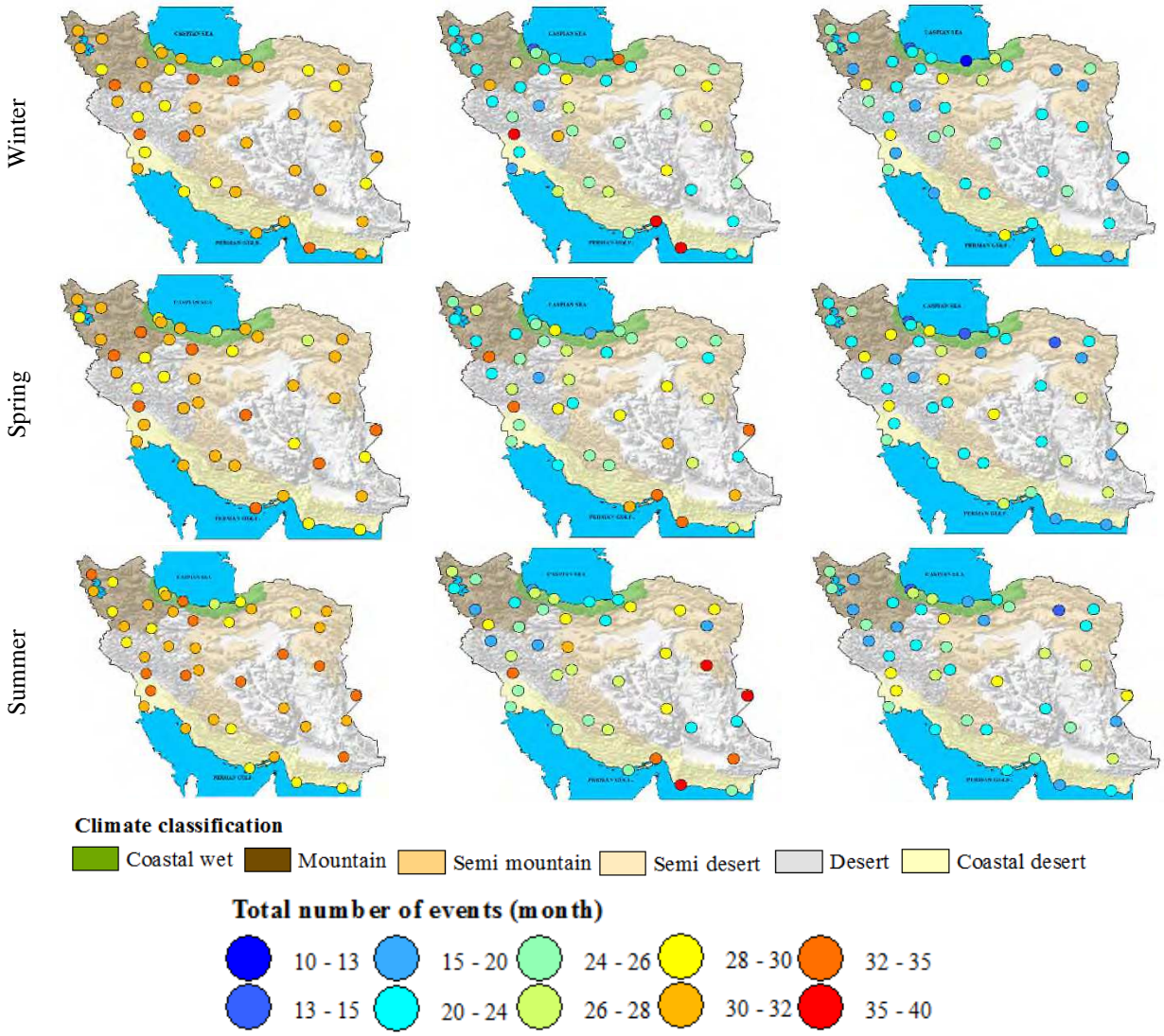


Fig. 6. Maps showing the total number of events based on SPI, SPEI and RDI using a threshold of -1 for each season of Iran

4. Conclusion

The phenomenon of climate change and its effects is one of the major challenges of water resources management in this century. It is important to determine how drought conditions change based on the diversity of different seasons and climates from various aspects, because many long-term plans require a drought forecasting system to monitor the future status of precipitation, drought and wet periods for different climates. Based on the results, in all studied climates, there is a high correlation SPI-RDI index pair (R=0.99). The lack of difference between SPI and RDI can be considered as not determining the ET_{ref} in the occurrence of drought. As a result, the SPI index can monitor drought alone by considering precipitation. In addition, in mountain, semi mountain, semi desert, desert and coastal desert climates, the correlation between SPI-SPEI and SPI-RDI varied (0.40 to 0.89), in which case the SPEI index is a suitable measure for these climates, because considering the two criteria of precipitation and ET_{ref}, the fitting of values is done with the help of a three-parameter distribution (three-parameter logistics) and as a result will have better control over the form of distribution.

The comparison of the results of all three indices in analyzing the trend of the number of drought events at different thresholds and in different seasons showed the trend of changes of three indices in the same zone, but the SPEI index compared to the other two indices in semi desert, desert and coastal desert climates reveals a higher frequency of drought and shows a faster response to moisture changes. Spatial analysis of drought trends using Pettit's test showed that drought trends are decreasing in most mountain and semi mountain climates and increasing in semi desert, desert and coastal desert climates. This severity was shown by the SPEI drought index first and then by the SPI and RDI indices with more severity.

The results of this study showed that the SPI index is a very simple index and does not require complex data, but, due to its high sensitivity to decrease and increase of precipitation, it can be said that it is an indicator that monitors more accurately. Therefore, it is suggested that after examining the efficiency of indices in the climates and in fact its localization, an important phenomenon such as drought must be investigated. Drought's increase or decrease has economic, social and political consequences. It is important to properly manage water resources in different climates and in different seasons, especially since income countries and their food security depend on climate diversity and water resources. It is generally suggested that in semi desert, desert and coastal desert climates the use of SPI is insufficient to monitor drought, and due to the role of temperature as a limiting factor for humidity and high ET_{ref}, the SPEI index should be used for effective and accurate monitoring of drought.

Funding The authors have no funding to report.

Conflict of interest The authors have no conflicts of interest to declare.

Availability of data and material All data used in this paper for Iran were extracted from metrological stations' data and can also be requested from the corresponding author.

Code availability Not applicable**.**

Author Contributions S.S. and M.M.G. prepared data and performed model runs, designed the study, interpreted the results, and wrote the manuscript.

Ethics approval Not applicable**.**

Consent to participate Not applicable**.**

Consent for publication Not applicable**.**

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