Meteorological drought in semi-arid regions: A case study of Iran (Postprint)

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Abstract

Drought occurs in almost all climate zones and is characterized by prolonged water deficiency due to unbalanced demand and supply of water, persistent insufficient precipitation, lack of moisture, and high evapotranspiration. Drought caused by insufficient precipitation is a temporary and recurring meteorological event. Precipitation in semi-arid regions ranges from 50 to 750 mm, differing from other regions. In general, the semi-arid regions in the west and north of Iran receive more precipitation than those in the east and south. This study utilized Terrestrial Climate (TerraClimate) data, including monthly precipitation, minimum temperature, maximum temperature, potential evapotranspiration, and the Palmer Drought Severity Index (PDSI) developed by the University of Idaho. The PDSI data was directly obtained from the Google Earth Engine platform. The Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI) were calculated at two different scales in time series and presented in spatial distribution maps. The results showed that normal conditions were common in the semi-arid regions of Iran over the majority of years from 2000 to 2020, according to a spatiotemporal study of the SPI at 3-month and 12-month time scales as well as the SPEI at 3-month and 12-month time scales. Moreover, the PDSI detected extreme dry years during 2000–2003 and in 2007, 2014, and 2018. In many semi-arid regions of Iran, the SPI at 3-month time scale is higher than the SPEI at 3-month time scale in 2000, 2008, 2014, 2015, and 2018. In general, this study concluded that the semi-arid regions underwent normal weather conditions from 2000 to 2020. Moderate, severe, and extreme dry occurred with a lesser percentage, gradually decreasing. According to the PDSI, during 2000–2003 and 2007–2014, extreme dry struck practically all hot semi-arid regions of Iran. Several parts of the cold semi-arid regions, on the other hand, only experienced moderate

Full Text

Preamble

Meteorological drought in semi-arid regions: A case study of Iran

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Abstract: Drought occurs in almost all climate zones and is characterized by prolonged water deficiency due to unbalanced demand and supply of water, persistent insufficient precipitation, lack of moisture, and high evapotranspiration. Drought caused by insufficient precipitation is a temporary and recurring meteorological event. Precipitation in semi-arid regions ranges from 50 to 750 mm, differing from other regions. In general, the semi-arid regions in the west and north of Iran receive more precipitation than those in the east and south. This study utilized Terrestrial Climate (TerraClimate) data, including monthly precipitation, minimum temperature, maximum temperature, potential evapotranspiration, and the Palmer Drought Severity Index (PDSI) developed by the University of Idaho. The PDSI data was directly obtained from the Google Earth Engine platform. The Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI) were calculated at two different scales in time series and presented in spatial distribution maps. The results showed that normal conditions were common in the semi-arid regions of Iran over the majority of years from 2000 to 2020, according to a spatiotemporal study of the SPI at 3-month and 12-month time scales as well as the SPEI at 3-month and 12-month time scales. Moreover, the PDSI detected extreme dry years during 2000–2003 and in 2007, 2014, and 2018. In many semi-arid regions of Iran, the SPI at 3-month time scale is higher than the SPEI at 3-month time scale in 2000, 2008, 2014, 2015, and 2018. In general, this study concluded that the semi-arid regions underwent normal weather conditions from 2000 to 2020. Moderate, severe, and extreme dry occurred with a lesser percentage, gradually decreasing. According to the PDSI, during 2000–2003 and 2007–2014, extreme dry struck practically all hot semi-arid regions of Iran. Several parts of the cold semi-arid regions, on the other hand, only experienced moderate to severe dry from 2000 to 2003, except for the eastern areas and wetter regions. The significance of this study is the determination of the spatiotemporal distribution of meteorological drought in semi-arid regions of Iran using strongly validated data from TerraClimate.

Keywords: meteorological drought; precipitation; Standardized Precipitation Index; Standardized Precipitation Evapotranspiration Index; Palmer Drought Severity Index; Iran

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1 Introduction

Drought occurs in almost all climate zones and is considered a major natural hazard (Zhang et al., 2019). It is characterized by prolonged water deficiency due to unbalanced demand and supply of water (Zhou et al., 2022), persistent insufficient precipitation, lack of moisture, and high evapotranspiration (Yang et al., 2018). Drought from lack of precipitation is a transient and recurring meteorological event (Beyaztas et al., 2018). As an uncertain natural phenomenon with an undefined onset, drought is among the most destructive natural occurrences on the planet, with global consequences that extend beyond regions with low average rainfall. Unlike other environmental disasters, its onset and progression are unnoticeable and gradual, albeit having cumulative and catastrophic impacts (Hamarash et al., 2022). Drought is classified into four types: meteorological (lack of precipitation), hydrological (deficiency in surface or subsurface streamflow), agricultural (deficiencies of soil moisture), and socioeconomic (inability to meet water resource demand) drought (Wang et al., 2019).

Droughts become observable after a prolonged period without precipitation, but their beginning, extent, and end are difficult to predict. Their characteristics in terms of intensity, magnitude, persistence, and spatial extent are complicated, which has motivated extensive efforts to develop drought analysis and monitoring methods (Vicente-Serrano et al., 2010). The first and most important issue faced when studying drought is determining appropriate drought indices. Numerous meteorological drought indices have been discovered and examined for use across different climate zones and at various time scales (Wang et al., 2019). The most widely utilized indices include the Palmer Drought Severity Index (PDSI), Standardized Precipitation Index (SPI), Effective Drought Index (EDI), Reconnaissance Drought Index (RDI), and the Standardized Precipitation Evapotranspiration Index (SPEI). Since drought threats are complex, no single index is appropriate for all places or tasks, making it critical to consider multiple indices to analyze sensitivity and accuracy (Banimahd and Khalili, 2013).

The SPI is primarily based on precipitation, is simple to compute, and has multiscalar properties that distinguish between different types of droughts. The PDSI is based on soil water balance and requires a wide range of data but cannot respond to the fundamental multi-scalar nature of drought. The SPEI is based on climatic water balance (the difference between precipitation (P) and evapotranspiration (ET)) calculated monthly or weekly. It integrates the SPI's multiscalar characteristics and straightforward calculation with the PDSI's sensitivity to changes in evaporation requirements induced by temperature variation and trends. The SPEI's key advantage is its flexibility to distinguish between various drought conditions, making it useful for monitoring and investigating drought features in the context of global warming (Tan et al., 2015). These indices are prioritized for detecting drought over various time scales, ranging from 3, 6, 9, 12, and 24 to 48 months. The SPI is widely employed worldwide because it depends only on precipitation data (Kazemzadeh and Malekian, 2016; Nasrollahi et al., 2018), while the SPEI outperforms other indices in evaluating drought characteristics, particularly in regions with humid, hyper-arid, semi-arid, and Mediterranean climates (Zarei et al., 2021).

The University of Idaho established Terrestrial Climate (TerraClimate) as a high-resolution dataset of monthly climate and climatic water balance for worldwide terrestrial surfaces, providing a global monthly precipitation time series from 1958 to the present (Hamed et al., 2021). TerraClimate can provide long-term monthly precipitation data for drought hazard assessment (Salvacion, 2022). Precipitation data from remote sensing products, especially TerraClimate, might offer a solution for semi-arid water balance challenges through a combination of rainfall measured at rain gauge stations and actual evapotranspiration from satellite products such as the moderate-resolution imaging spectroradiometer (MODIS) Global Terrestrial Evapotranspiration Product (MOD16) and the Global Land Evaporation and Amsterdam Model (GLEAM). Examination of these products is particularly essential since information from remote sensing and spatial databases can lead to more realistic hydrological variables (Neto et al., 2022). According to Hamed et al. (2021), TerraClimate demonstrates the best performance in South Egypt against gauge records compared to other products such as the Global Land Data Assimilation System (GLDAS)-Noah Model, European Reanalysis (ERA5), and Climatologies at high resolution for the Earth's land surface areas (CHELSA). Araneda et al. (2020) assessed TerraClimate datasets as alternative data sources for in situ measurements of hydrometeorological variables and proved that TerraClimate products are an appropriate complementary data source. Additionally, TerraClimate products excel at estimating the spatial distribution and long-term mean actual evapotranspiration (Huerta et al., 2020) and can substitute for ground data where such data are difficult to obtain.

While many studies investigate drought based on indices, few rely solely on TerraClimate. Therefore, the objectives of this study are to evaluate the spatiotemporal distribution of meteorological drought conditions in Iran and to assess drought in semi-arid regions using reliable TerraClimate data. TerraClimate is used because it is a well-known dataset providing monthly climate and climatic water balance for global terrestrial surfaces since 1958, has strong validation with station-based observations, and provides data on a global scale with high spatial resolution and time-varying data (Abatzoglou, 2021). The novel contribution of this study is the determination of the spatiotemporal distribution of meteorological drought in semi-arid regions of Iran using validated data from TerraClimate.

2.1 Study area

According to the Köppen climate classification, Iran has both cold and hot semi-arid regions covering a large area and is considered the largest semi-arid region in the world, with a geographical position of 25°N–40°N and 45°E–60°E. It consists of two different climate semi-arid zones: cold and hot semi-arid regions, stretching from Bushehr Province in the southwest to North Khorasan Province in the northeast, and from small parts of Sistan and Baluchestan Province in the southeast to Kermanshah Province in the northwest. While province names are used in this study, they may include small portions located in semi-arid regions, such as Ilam, Esfahan, Qom, Sistan and Baluchestan, and Kurdistan provinces, or might encompass entire provinces considered semi-arid, such as Razavi Khorasan, South Khorasan, Yazd, and Kerman provinces. Semi-arid regions vary in the literature (Rahimi and Laux, 2020), so this study used climate maps of Iran to extract semi-arid regions based on Peel et al. (2007).

2.2 Precipitation

Precipitation in semi-arid regions ranges between 50 and 750 mm, differing from other regions. In general, the western and northern semi-arid regions of Iran receive more precipitation than the east and south [Figure 1: see original paper]. From 2000 to 2014, annual total precipitation ranged from 50 to 250 mm in the southeast and central semi-arid region, while precipitation was higher in the north, northwest, and southwest, ranging between 300 and 550 mm. More precipitation fell in northwest and south Iran in 2018 and 2019, respectively, with 2019 being the wettest year for the entire region. A previous study showed a similar trend in precipitation amount in the semi-arid region, with an average annual precipitation of 250 mm (Zoljoodi and Didevarasl, 2013).

2.3 Data sources

This study used monthly precipitation, minimum temperature, maximum temperature, evapotranspiration, and PDSI data obtained from the TerraClimate product developed by the University of Idaho on the Google Earth Engine platform. Table 1 provides the characteristics of the TerraClimate dataset with their temporal and spatial resolution. The nearest neighbor method was used to resample the data resolution to a spatial resolution of 1 km, while the time resolution remained monthly as provided by TerraClimate. TerraClimate is a monthly-timestep worldwide gridded dataset of meteorological and water balance indicators from 1958 to the present. Its fine spatial resolution, worldwide range, and extended length make it a unique dataset that fills a gap in climate data. TerraClimate uses climatically aided interpolation, combining high-spatial resolution climatological normals from the WorldClim dataset with coarser resolution time-varying information from Climate Research Unit time series data version 4.0 (CRU TS4.0) and the Japanese 55-year reanalysis (JRA-55) (Abatzoglou et al., 2018a). For most worldwide land surfaces, temporal data of temperature, precipitation, and evapotranspiration are acquired from CRU TS4.0, while JRA-55 data is used in geographic areas where CRU data had no climate stations contributing (including all of Antarctica, parts of Africa, parts of South America, and scattered islands). TerraClimate has been successfully utilized in previous drought analyses and demonstrated to be an excellent complementary data source (Araneda et al., 2020), with the highest and greatest spatial resolutions (Neto et al., 2022) and excellent assessment of the spatial distribution of actual evapotranspiration (Huerta et al., 2020).

2.4 Methods

Drought is a multi-scalar occurrence, so three well-known indices (PDSI, SPEI, and SPI) are used for monitoring meteorological drought in semi-arid regions of Iran. The SPI is generally recognized because it can be calculated at various timescales to monitor droughts concerning specific water resources. It is a precipitation-based index calculated using precipitation over a certain region (McKee et al., 1993). The SPEI monitors drought and is related to the SPI but includes calculations of moisture losses to the atmosphere due to evapotranspiration. The SPEI is determined at various time scales depending on precipitation and potential evapotranspiration changes (Vicente-Serrano et al., 2010) and is prioritized for drought detection over periods including 3, 6, 9, 12, 24, and 48 months. The PDSI requires extensive data and is based on soil water balance, but it is unable to react to drought's fundamental multi-scalar characteristics. Its important variable is weather data, which helps diagnose long-term drought, and it was developed to manage drought in semi-arid and dry sub-humid regions (Palmer, 1965).

2.4.1 Palmer Drought Severity Index (PDSI)

The PDSI data was obtained from the Google Earth Engine platform. The PDSI is one of the most well-known and commonly used drought indices (Palmer, 1965), requiring monthly or weekly mean temperatures, total precipitation, soil moisture content (e.g., available water holding capacity), and potential evapotranspiration amounts for the soil moisture balance algorithm. Potential evapotranspiration and latitude are required for the PDSI (Tatli and Türkeş, 2011). Although the PDSI was initially not contained in the TerraClimate dataset, it was afterward added (see http://www.climatologylab.org/TerraClimate.html). The PDSI from TerraClimate employs Palmer's standard approach (Palmer, 1965), which uses both reference evapotranspiration and monthly precipitation in its calculation (Kodandapani and Parks, 2019). In addition to precipitation data and potential evapotranspiration values, the soil's water holding capacity must be provided for PDSI calculation. The soil's water holding capacity is present in soil moisture storage, divided into two layers: the upper layer holds 25.4 mm of available water holding capacity at field capacity, while the underlying layer holds available water holding capacity differently depending on soil characteristics (Tall, 2008). Hence, the PDSI can monitor long-term meteorological droughts.

2.4.2 Standard Precipitation Index (SPI)

The SPI was introduced to detect dry and wet periods and is an optimum index for monitoring drought at different time scales from 1 month to 24 months, developed by McKee et al. (1993) and recommended as a standard drought index by the World Meteorological Organization. Only precipitation data for about 20 years or more is required to show dry and wet conditions (Tan et al., 2015). This study employed monthly precipitation data during 2000–2020 to calculate monthly SPI values for semi-arid regions in Iran. The SPI can be determined for any place based on long-term precipitation records for the selected period. The long-term data is fitted to a gamma probability distribution, which is then transformed into a normal distribution, yielding a zero-mean SPI for the given location and period. Negative and positive SPI values indicate below-average and above-average precipitation, respectively. Dryness is indicated by precipitation below the median, while wetness is indicated by precipitation above the median, allowing the SPI to evaluate and track both wet and dry periods in a given area (Tefera et al., 2019). The gamma probability density function was first used for a specific frequency distribution of precipitation data in the proposal of McKee et al. (1993) to measure climate and drought change. A gamma distribution is frequently employed to describe temporally averaged precipitation statistics (Martinez-Villalobos and Neelin, 2019; Liu et al., 2021). The calculation process is as follows:

where p(x) is the gamma probability density function for a given frequency distribution of precipitation; α is a shape parameter (α>0); β is a scale parameter (β>0); x is the amount of precipitation (x>0; mm); $\Gamma(\alpha)$ is the gamma function; SPI is the Standardized Precipitation Index; xi is rainfall in year i; $\bar{x}$ is long-term average rainfall; and σ is the standard deviation.

The SPI can be calculated for any duration from 1 month to 24 months depending on research interest: a time scale of 1 month to 3 months can show meteorological drought; a time scale of 6 months is appropriate for agricultural drought; and more than 6 months is suitable for hydrological drought, revealing shortages of groundwater, reservoir, and streamflow water and illustrating soil moisture conditions due to lack of precipitation (Tefera et al., 2019).

2.4.3 Standardized Precipitation Evapotranspiration Index (SPEI)

Vicente-Serrano et al. (2010) introduced the SPEI as a drought index responsive to both precipitation and air evaporative demand that can be estimated on various time scales. The SPEI enhances the commonly used SPI by including calculations of moisture losses to the atmosphere due to evapotranspiration. Monthly potential evapotranspiration was calculated according to the Food and Agriculture Organization-56 Penman-Monteith method, allowing the SPEI to achieve excellent outcomes regarding drought, streamflow, and soil moisture monitoring (Zhang et al., 2018). As shown in Table 2, two values represent dry and wet conditions, with negative values representing dry conditions and positive values representing wet conditions.

Reference evapotranspiration was calculated using the Penman-Monteith approach (Allen et al., 1998). The estimation of monthly potential evapotranspiration is the first step in calculating SPEI. Then, the monthly deficit of potential evapotranspiration is calculated based on the water balance equation:

where Di is the moisture deficit in month i from the monthly difference between precipitation and PET; Pi is precipitation in month i (mm); and PETi is potential evapotranspiration in month i (mm).

The values of monthly deficit of potential evapotranspiration are aggregated at different time scales as follows:

where D is the moisture deficit (mm); k is the timescale of aggregation; n is the calculation month; i is a given month; P is precipitation (mm); and PET is potential evapotranspiration (mm).

The difference in the water balance is normalized as a log-logistic probability distribution to determine the SPEI value. The probability density function is expressed by:

where f(x) is the probability density function of a three-parameter log-logistic distributed variable; and γ is an origin parameter (γ>D). The probability distribution function can be expressed as:

where F(x) is the cumulative distribution function of the D values.

where SPEI is the Standardized Precipitation Evapotranspiration Index; C0, C1, C2, d1, d2, and d3 are constants (C0=2.515517, C1=0.802285, C2=0.010328, d1=1.432788, d2=0.189269, and d3=0.001308); and W is probability-weighted moments.

2.4.4 Spatial distribution analysis

The inverse distance weighting method was used to estimate both SPI and SPEI distributions spatially and temporally. This method can be used for multivariate interpolation, based on the assumption that an un-sampled point's attribute value is the weighted average of known values in the area. This technique uses values from a distributed set of known points to assign values to unknown points, where the value at the unknown point is the weighted sum of the values of known points. Inverse distance weighting is a deterministic method for multivariate interpolation (Chen and Liu, 2012) that utilizes distance weighting to interpolate spatial data.

The inverse distance weighting method, also known as inverse distance-based weighted interpolation, uses a weighted mean of adjacent observations to estimate the known value at point x. The calculated equation is as follows:

where Z(x) is the predicted value at location x; m is the number of nearest known points surrounding location x; zi is the known value; wi is the weighting of each point; x is an interpolated and arbitrary point; xi is an interpolated and known point; and β greater than 0 corresponds to the Euclidean distance. The inverse distance determines the degree to which nearer points are preferred over more distant points. The number of surrounding points decides whether global or local weighting is applied. If the point coincides with an observation location, the observed value is returned to avoid infinite weights.

In this study, both SPEI and SPI were calculated automatically using the SPEI package in R statistical software at 3-month and 12-month time scales to obtain a complete picture of drought occurrences in the study area.

3 Results

The semi-arid regions of Iran stretch from the southeast to the northwest based on the Köppen climate classification. Approximately 25 provinces lie in semi-arid regions in Iran, though several provinces have only small portions with semi-arid weather conditions. The SPI and SPEI in Iran vary from one place to another because Iran has two different semi-arid regions: cold and hot semi-arid zones.

3.1 Temporal and spatial analysis of the PDSI in semi-arid regions of Iran

The PDSI is separated into two different semi-arid regions based on cold and hot semi-arid weather. Figures 2 and 3 show that cold semi-arid regions have lower PDSI range values (from 2.5 to –5.0 in most provinces) than hot semi-arid regions, indicating fewer dry years in cold semi-arid regions compared to hot semi-arid regions. In almost all hot semi-arid regions, extreme dry occurred from 2000 to 2003 and from 2007 to 2014. In contrast, several areas in cold semi-arid regions only experienced moderate to severe dry from 2000 to 2003, except in West Azerbaijan and North Khorasan provinces, which experienced extreme dry. Extreme wet conditions occurred in 2019 in approximately all hot and cold semi-arid regions of Iran.

Semi-arid regions in both East Azerbaijan and West Azerbaijan provinces differ from other provinces in the southeast and southwest regarding dry years. For instance, unlike other cold semi-arid regions, a drought occurred in 2020. Although Mazandaran Province had several dry years (e.g., in 2008 and during 2000–2003 and 2014–2018), it had many wet years compared to other provinces because it lies south of the Caspian Sea, which leads to more precipitation. Razavi Khorasan Province fluctuated from severe dry to moderate dry in almost all years because precipitation fluctuated between 200 and 350 mm, as shown in Figure 1, except in 2019 and 2020, which recorded high precipitation and wet years. Several provinces may experience different drought conditions because they are located in both cold and hot semi-arid regions, such as Esfahan, Fars, Hamadan, Hormozgan, Kerman, Markazi, Sistan and Baluchestan, and South Khorasan provinces. Drought was more frequent in some provinces such as Razavi Khorasan, South Khorasan, Kerman, Fars, Esfahan, Semnan, Sistan and Baluchestan, and Lorestan because these provinces had less precipitation, specifically Razavi Khorasan, Semnan, Esfahan, South Khorasan, Yazd, and Kerman provinces (Figs. 2 and 3).

3.2.1 SPI at 3-month time scale and SPEI at 3-month time scale

The monthly characteristics of both SPI at 3-month time scale (SPI-3) and SPEI at 3-month time scale (SPEI-3) fluctuated, showing variation of dry and wet conditions from month to month. The SPEI-3 and SPI-3 fluctuated dramatically in approximately the same way in most semi-arid regions (Figs. 4 and S1). However, the SPEI-3 was slightly different in several years because it requires more data, such as evapotranspiration and temperature, resulting in different values. Evapotranspiration and temperature change with seasons, causing variation in SPEI values from year to year. The SPI-3 exceeded −2.0 (extremely dry) in both Alborz and East Azerbaijan provinces in different years (2008, 2011, and 2018). The SPEI-3 was negatively higher than the SPI-3 in 2019 in Alborz Province due to high temperature and potential evapotranspiration. The SPEI-3 was positively high in several provinces in 2019, including Bushehr, Fars, Ilam, Kermanshah, Kohgiluyeh and Boyer-Ahmad, Markazi, Lorestan, and Qom provinces, due to low evapotranspiration and increased precipitation. Nevertheless, the SPI-3 was high or equal in value to the SPEI-3 in all semi-arid regions in both positive and negative directions [Figure 4: see original paper].

In many semi-arid regions of Iran, the SPI-3 was higher than the SPEI-3 in 2000, 2008, 2014, 2015, and 2018, though the entire semi-arid region was recorded as extremely dry in 2000. Although the SPEI-3 was lower than the SPI-3 or had the same values throughout the study periods, the SPEI-3 surpassed the SPI-3 in Hormozgan, Fars, Bushehr, Kerman, Kohgiluyeh and Boyer-Ahmad, and South Khorasan provinces from 2016 to 2018 due to high evapotranspiration. Several provinces experienced high SPEI-3 in 2018 and 2020, including East Azerbaijan, West Azerbaijan, Ilam, Kermanshah, Markazi, Lorestan, Mazandaran, Qom, Semnan, Tehran, and Yazd provinces (Figs. 4 and S1). Kerman Province had the highest SPEI-3 in the entire study area in 2000 due to the lowest precipitation and high temperature. Reversed values were recorded in both SPI-3 and SPEI-3 in certain years: positive SPI-3 and negative SPEI-3 were recorded in several provinces such as Fars, Kerman, and Hormozgan, indicating these provinces experienced high temperature despite receiving sufficient precipitation. Both SPEI-3 and SPI-3 showed a 3-month lag, revealing seasonal drought characteristics that lead to negative and positive fluctuation values in almost all years. Dry and wet conditions were witnessed in almost all years, and for a few years, values exceeded −2.0, indicating extremely dry conditions.

3.2.2 SPI at 12-month time scale and SPEI at 12-month time scale

Figure 5 illustrates the SPI-12 and SPEI-12 in semi-arid regions of Iran. There are noticeably small differences between the two indices because the SPEI-12 considers evapotranspiration as a factor in drought impacts. A greater negative SPEI-12 value means evapotranspiration is high due to high temperature, while a greater positive value means the region receives sufficient precipitation simultaneously with low temperature. For example, in 2001, 2017, and 2018, the SPEI-12 showed negative values in several regions, indicating high evapotranspiration. Several major dry years occurred in semi-arid regions, including 2000–2003, 2007, 2009, 2011, 2014, 2015, and 2018. All semi-arid regions might not reflect drought similarly because they include two different climate zones (cold and hot semi-arid), causing slight differences from southeast to northwest.

The SPEI-12 was slightly higher compared to the SPI-12 in several provinces from 2000 to 2003, including Alborz, Esfahan, Golestan, Hamadan, Ilam, Kermanshah, Lorestan, Markazi, Mazandaran, North Khorasan, Semnan, and Tehran provinces, clearly showing these provinces experienced high evapotranspiration due to increased temperature. Moderate and severe dry occurred in almost all semi-arid regions during 2001–2002, except West Azerbaijan, East Azerbaijan, Razavi Khorasan, and South Khorasan provinces, which had extremely dry years based on both indices. Values of −2.0 were recorded in both indices in all provinces since 2008. The SPEI-12 and SPI-12 showed extreme and severe dry years during 2010–2011 in almost all study areas except Mazandaran Province due to its location near the Caspian Sea. The SPEI-12 was higher than the SPI-12 in 2008 in Hormozgan Province because it is located near the Persian Gulf, where temperature is very high. The driest years in Bushehr Province were 2010 and 2011 based on the SPI-12 due to precipitation deficit. In the last decade, several periods in semi-arid regions experienced severe to extreme dry in 2013 and during 2015–2016 and 2017–2018. Extreme dry hit several provinces including Mazandaran, Ilam, Lorestan, Kermanshah, Qom, and Tehran provinces in 2015. The SPEI-12 showed extreme dry in Hormozgan, Kerman, Fars, South Khorasan, and North Khorasan provinces during 2017–2018, while the SPI-12 showed moderate dry, indicating high temperature was dominant in these provinces. Alborz Province was extremely dry in 2009 and 2018 and severely dry in 2001, 2003, and 2015 (Fig. S2). Moderate dry years were frequent and recorded in both indices, with longer dry years occurring from 2000 to 2003 and from 2014 to 2018 in some semi-arid regions. Dryness occurred more frequently between 2010 and 2020 compared to 2000–2010, spreading across most areas where precipitation variability is not significant [Figure 5: see original paper].

3.3 Frequency of dry and wet periods

Analysis of dry and wet events over the last 20 years found that both SPI-12 and SPEI-12 are approximately similar in the extent of dry and wet months. Figure 6 shows that most provinces have normal weather conditions, though several provinces recorded slightly lower frequencies of normal conditions, such as Kermanshah, Bushehr, and Kurdistan provinces, which instead witnessed higher moderate wet periods due to receiving higher precipitation compared to other provinces in the same climatic zone. Although extreme dry reached its lowest values in most provinces, several provinces displayed slightly more extreme dry, such as Esfahan, Fars, Kohgiluyeh and Boyer-Ahmad, and Markazi provinces. According to the SPI-3, the second highest periods were moderate wet and dry. Figure 6b shows the SPEI-3 in semi-arid regions where near-normal regions had the highest value, while moderate wet and dry were the second highest values in all provinces. Figures 6b and 6c show that near-normal was also the highest value in both indices. Figures 6c and 6d illustrate that both extreme wet and dry classes were slightly higher in several places than other semi-arid regions, despite dry and wet conditions being witnessed in almost all years [Figure 6: see original paper].

3.4 Drought events analysis based on spatial distribution of the SPEI and the SPI

Spatial distribution analysis was conducted in both winter and summer seasons, as well as wet and dry seasons, for drought detection. Although drought is not specific to one season, it is significant to display dry and wet conditions in winter and summer in semi-arid regions of Iran, as both seasons could reveal drought in the region. The SPI-12 map showed that the region has undergone noticeably normal conditions in general, though moderate to severe dry occurred in several years. For instance, moderate dry was recorded in the winter of 2002 in several provinces such as Razavi Khorasan, North Khorasan, Qom, West Azerbaijan, and East Azerbaijan provinces, and again in the summer of 2012 in Kermanshah and Ilam provinces. Severe and moderate dry occurred in 2015 and 2017 in north and southwest Iran. Most dry seasons occurred in north and southwest Iran due to insufficient precipitation. The wettest season was the winter of 2020, the wettest recorded in the last 20 years, though it started at the beginning of 2019 (Fig. S3). The SPEI-12 map indicated that near-normal, moderate dry, severe dry, moderate wet, and severe wet conditions occurred in several years (Fig. S4). Moderate to severe dry conditions were recorded in 2002 in east and northeast Iran, including Kerman, Sistan and Baluchestan, Semnan, Razavi Khorasan, North Khorasan, Tehran, and Kermanshah provinces, with extremely dry conditions in West Azerbaijan and East Azerbaijan provinces. Moderate wet conditions occurred in several years, such as 2002 in southwest Iran, 2007 in southeast and northwest Iran, and 2012 in north Iran.

In 2015, moderate to severe dry was detected in both seasons in northwest provinces from Mazandaran Province to Kermanshah Province in west Iran, except in West Azerbaijan and East Azerbaijan provinces. In summer, severe drought hit Sistan and Baluchestan and Kerman provinces. In 2017, moderate dry occurred sparsely in the region, but the largest area of moderate and severe dry was seen in summer in southwest Iran, including Fars, Bushehr, and Kohgiluyeh and Boyer-Ahmad provinces. This continued into the winter of 2019, especially in southeast Iran, while wet conditions appeared in different years such as 2005, 2007, 2010, 2012, 2019, and 2020.

4 Discussion

Three indices are used for identifying meteorological drought in semi-arid regions of Iran: SPI, SPEI, and PDSI. The PDSI has been used to identify meteorological drought in several studies (Dash et al., 2012; Dehghan et al., 2020; Tao and Zhang, 2020). Its main variables are weather data, making it suitable for detecting drought over longer periods since it considers average monthly data based on the principle of balance between supply and demand for moisture (Karl, 1983). Drought based on the PDSI is frequent and occurs in all semi-arid regions of Iran. Negative values, indicating dry weather, occurred from 2000 to 2004 in all semi-arid regions with low precipitation and high temperature, similar to previous studies (Darand, 2015; Kheyri et al., 2021) that confirmed Iran experienced a dry period between 2000 and 2004. This is also similar to a study in Ardebil Province in northwestern Iran by Kazemzadeh and Malekian (2016), which detected meteorological drought during 2000–2004, 2007–2008, and 2010 based on the SPI. In this study, meteorological drought occurred in 2008 and during 2010–2011 and 2014–2018, from Hamadan and Qom provinces in cold semi-arid regions to Lorestan, Esfahan, Fars, Markazi, Kermanshah, Kohgiluyeh and Boyer-Ahmad, Razavi Khorasan, and Semnan provinces in hot semi-arid regions. These results align with a study in Fars Province (Dehghan et al., 2020), which showed drought in 2000–2001, 2008, and 2010 and predicted increasing drought after 2014. Another consistent study recorded the same dry years and precipitation deficit in 2000, 2001, 2008, and 2010 in Fars Province (Hossein et al., 2014). From 2008 to 2018, the same drought periods affected Golestan, Yazd, and Tehran provinces, except from 2012 to 2013.

The SPEI and SPI are both used for drought variation and monitoring, but the SPI neglects evaporation impacts, whereas the SPEI incorporates both precipitation and evapotranspiration, making it appropriate for semi-arid regions. Both SPI and SPEI varied often around 0.0 with a large range due to short-term climatic change, clearly showing subtle shifts in water profit and loss at 3-month time scale (Pei et al., 2020). This study showed that semi-arid regions underwent normal weather conditions from 2000 to 2020, with moderate, severe, and extreme dry occurring at lower percentages that gradually decreased. For instance, moderate dry has a higher percentage than both severe and extreme dry in almost all semi-arid regions in both SPI and SPEI. Similar research by Bari Abarghouei et al. (2011) demonstrated increasing severity of meteorological drought based on the SPI, and another study found increased meteorological drought based on the Reconnaissance Drought Index (Kousari et al., 2014). Although both extreme dry and extreme wet had the lowest percentages in both indices, extreme dry and extreme wet rarely occurred in SPEI-12 and SPI-12, respectively, due to climatic characteristics. According to calculated SPEI values, the normal class of drought severity had maximum occurrence frequency (approximately 60%–70% during the studied years), while extreme wet had the lowest occurrence frequency (less than 2% during the studied years) at all stations and time scales. SPI-based results for occurrence frequency of different drought severity classes were nearly identical to those of the SPEI (Zarei et al., 2021). Both indices on different scales showed no significant variation from each other in almost all regions, similar to a study by Sharafati et al. (2020) that showed high agreement between SPI and SPEI, indicating that meteorological drought is more responsive to precipitation than potential evapotranspiration. The excellent correlations also implied that results obtained using SPI would not differ if a similar analysis used SPEI. However, SPEI was higher than SPI in several regions in different years, signifying high potential evapotranspiration, especially in 2018. Zarei et al. (2021) noted that potential evapotranspiration was high in some provinces due to high temperature and low precipitation.

Spatial distribution is the most important key to visually evaluate drought events and is a widespread technique to understand the drought phenomenon, widely acknowledged by drought professionals (Andreadis et al., 2005; Guo et al., 2017). This study considers both SPEI and SPI optimal for showing specific drought because whenever SPI is computed at short periods in regions with minimal seasonal precipitation, it might produce large positive or negative results that could be misleading (Sönmez et al., 2005; World Meteorological Organization, 2012; Guo et al., 2017). In SPI-3, normal conditions are predominant in all years except 2000, 2008, 2012, 2015, and 2017, consistent with a study by Zarei et al. (2017). A previous study in central and southern Iran illustrated that most semi-arid regions prone to high drought frequencies likely suffer drought with return periods between 5 to 10 years based on SPI-12 (Alijanian et al., 2019). The current study showed that drought did not occur in all regions in the same year but only in specific regions because precipitation and evapotranspiration were not uniform, as shown in Figures S3 and S4. Although moderate to extreme dry occurs in almost all years, it affects only specific areas, not all semi-arid regions. Normal drought dominates most semi-arid regions. Contrary to these results, a study by Nasrollahi et al. (2018) illustrated that moderate and severe dry have the highest percentages in Semnan Province. Furthermore, the SPEI normal class was the highest value and extreme class the lowest, consistent with Zarei et al. (2021) that demonstrated normal class as the highest value and extreme wet class as the lowest. Nejadrekabi et al. (2022) conducted a study in Khuzestan Province on the border of our study area and found that drought severity has increased since 2012, hitting the southern and southeastern parts based on SPEI. Drought occurred in the summer of 2017 and winter of 2019 near Khuzestan Province. Finally, our results are nearly consistent with Karakani et al. (2021), which used SPI and illustrated that the Middle East underwent near-normal conditions in most years between 2001 and 2017, but 2001, 2006, and 2008 were recorded as moderate dry.

5 Conclusions

Drought is a serious natural hazard that occurs in practically all climates. TerraClimate was used as an alternative to station data to show drought in semi-arid regions of Iran, considered the largest semi-arid regions in the world. The PDSI findings showed that cold semi-arid regions have lower PDSI range values than hot semi-arid regions, ranging from 2.5 to –5.0 in most regions. This means that semi-arid regions underwent normal weather conditions from 2000 to 2020, with moderate, severe, and extreme dry occurring at lower percentages that gradually decreased. For example, moderate dry has a higher percentage than severe and extreme dry in almost all semi-arid regions. According to SPI-12 and SPEI-12, years with moderate dry are frequently recorded in both indices, and the longest dry years occurred from 2000 to 2003 and from 2014 to 2018 in most semi-arid regions. Moreover, years with extreme dry and severe dry are recorded in 2007, 2008, 2011, and 2017. According to the spatial distribution of SPEI and SPI, semi-arid regions have experienced near-normal conditions in general. However, it is determined that TerraClimate data is suitable as an alternative for areas where in-situ data is unfeasible, especially for desert, arid, and semi-arid regions in future studies.

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Appendix

Fig. S1 Standard Precipitation Index (SPI) at 3-month time scale (SPI-3) and Standardized Precipitation Evapotranspiration Index (SPEI) at 3-month time scale (SPEI-3) in several semi-arid regions of Iran during 2000–2020. (a) Alborz Province; (b) Sistan and Baluchestan Province; (c) Golestan Province; (d) Hamadan Province; (e) Kurdistan Province; (f) Esfahan Province; (g) Kohgiluyeh and Boyer-Ahmad Province; (h) Lorestan Province; (i) Tehran Province; (j) Yazd Province.

Fig. S2 SPI at 12-month time scale (SPI-12) and SPEI at 12-month time scale (SPEI-12) in several semi-arid regions of Iran during 2000–2020. (a) Alborz Province; (b) Sistan and Baluchestan Province; (c) Golestan Province; (d) Hamadan Province; (e) Kurdistan Province; (f) Esfahan Province; (g) Kohgiluyeh and Boyer-Ahmad Province; (h) Lorestan Province; (i) Tehran Province; (j) Yazd Province.

Fig. S3 Spatial and temporal distribution of SPI-12 in winter and summer in semi-arid regions of Iran. (a) Winter 2002; (b) Summer 2002; (c) Winter 2005; (d) Summer 2005; (e) Winter 2007; (f) Summer 2007; (g) Winter 2010; (h) Summer 2010; (i) Winter 2012; (j) Summer 2012; (k) Winter 2013; (l) Summer 2013; (m) Winter 2015; (n) Summer 2015; (o) Winter 2017; (p) Summer 2017; (q) Winter 2019; (r) Summer 2019; (s) Winter 2020; (t) Summer 2020.

Fig. S4 Spatial and temporal distribution of SPEI-12 in winter and summer in semi-arid regions of Iran. (a) Winter 2002; (b) Summer 2002; (c) Winter 2005; (d) Summer 2005; (e) Winter 2007; (f) Summer 2007; (g) Winter 2010; (h) Summer 2010; (i) Winter 2012; (j) Summer 2012; (k) Winter 2013; (l) Summer 2013; (m) Winter 2015; (n) Summer 2015; (o) Winter 2017; (p) Summer 2017; (q) Winter 2019; (r) Summer 2019; (s) Winter 2020; (t) Summer 2020.

Note: Figure translations are in progress. See original paper for figures.