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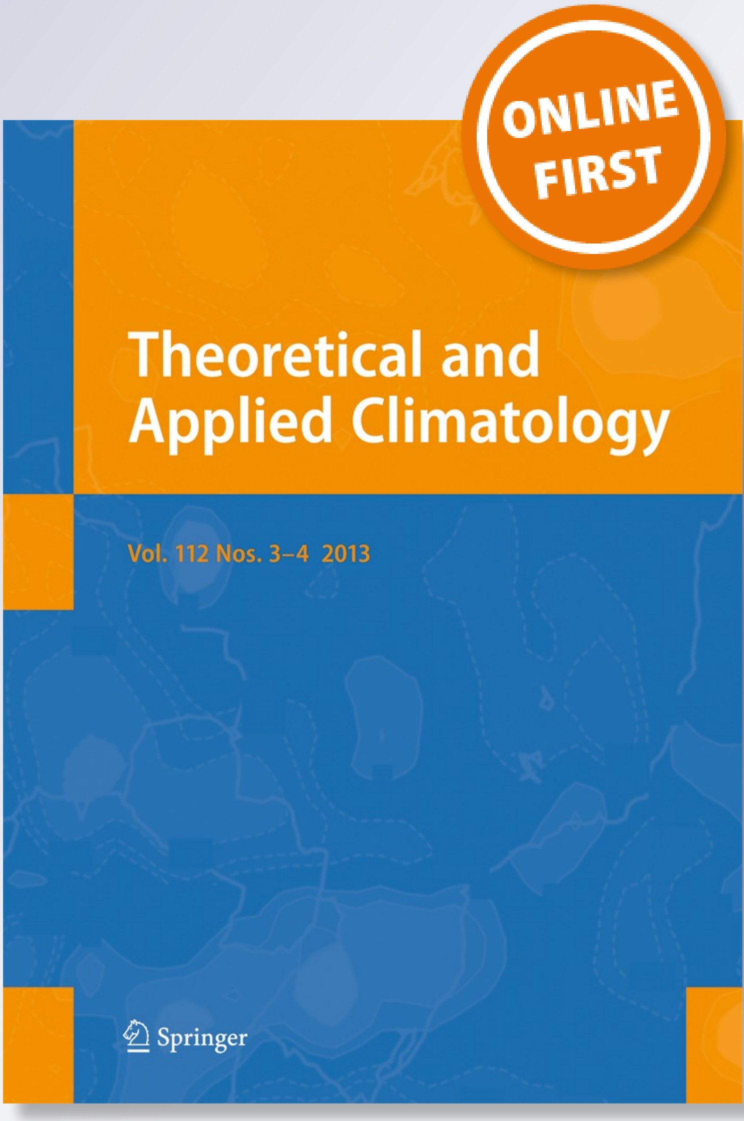

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ORIGINAL PAPER

Observed spatiotemporal characteristics of drought on various time scales over the Czech Republic

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Abstract This paper analyses the observed spatiotemporal characteristics of drought in the Czech Republic during the growing season (April to September) as quantified using the Standardised Precipitation Evapotranspiration Index (SPEI) on various time scales. The SPEI was calculated for various lags (1, 3, 6, 12, and 24 months) from monthly records of mean temperature and precipitation totals using a dense network of 184 climatological stations for the period 1961–2010. The characteristics of drought were analysed in terms of the temporal evolution of the SPEI, the frequency distribution and duration of drought at the country level, and for three regions delimited by station altitude. The driest and the wettest years during the growing season were identified. The frequency distribution of the SPEI values for seven drought category classes (in per cent) indicates that normal moisture conditions represent approximately 65 % of the total SPEI values for all time scales in all three regions, whereas moderate drought and moderate wet conditions are almost equally distributed around 10.5 %. Differences in extremely dry conditions (5 %) compared with extremely wet conditions (1.5 %) were observed with increasing SPEI time scales. The results of the non-parametric Mann–Kendall trend test applied to the SPEI series indicate prevailing negative trends (drought) at the majority of the stations. The percentage of stations displaying a significant negative trend for the 90, 95, 99, and 99.9 % confidence levels is approximately 40 %. An Empirical Orthogonal Functions (EOF) analysis was used to identify the principal patterns of variability of the SPEI during the growing season that accounted for the highest amount of statistical variance. The variance explained by the leading EOF range 66 to 56 %, whereas for EOF2 and EOF3, the value is between 7 and 11 % and between 4 and 7 %, respectively, for the SPEI is calculated for 1- to 24-month lags.

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1 Introduction

Drought is one of the most complex natural hazards, with impacts on agriculture, water resources, natural ecosystems, and society. The negative societal consequences of drought include extreme economic losses, famine, epidemics, and land degradation (Beguería et al. 2010). However, few studies have characterised the complexity of drought phenomena at local, regional, or national scales to document its impact and track trends in regional sectors to help decision makers improve their level of preparedness and adopt appropriate policies for impact mitigation and adaptation to drought threats (Wilhite et al. 2007). Drought can be classified into

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three types (Dai 2011a): (1) *meteorological drought* is a period of months to years with below-normal precipitation. It is often accompanied by above-normal temperatures and precedes and causes other types of droughts. (2) *Agricultural drought* is a period with dry soils that results from below-normal precipitation, intense but less frequent rain events, or above-normal evaporation, all of which lead to reduced crop production and plant growth. (3) *Hydrological drought* occurs when river streamflow and water storage in aquifers, lakes, or reservoirs fall below long-term mean levels. Hydrological drought develops more slowly because it involves stored water that is depleted but not replenished. A lack of precipitation often triggers agricultural and hydrological droughts, but other factors, including more intense but less frequent precipitation, poor water management, and erosion, can also cause or enhance these types of droughts.

One category of drought studies addresses the causes of drought and the search to improve knowledge of the large-scale atmospheric circulation associated with drought occurrences (e.g. Jones et al. 1996; Chiew et al. 1998; Barlow et al. 2002; Girardin and Tardif 2005). A second category of studies is oriented towards the assessment of the probability of drought occurrence for various degrees of severity and spatial distributions (e.g. Bravar and Kavvas 1991; Tallaksen 2000; Briffa et al. 2009; Potop and Soukup 2009; Bordi et al. 2009; Özger et al. 2009; Beguería et al. 2010). A third category of studies is focused on the assessment and understanding of the impact of drought (e.g. Maracchi 2000; Narasimhan and Srinivasan 2005; Mavromatis 2007; Lorenzo-Lacruz et al. 2010; Potop et al. 2010; Potop 2011). The fourth category addresses societal responses to drought threats and appropriate strategies to mitigate and adapt to the impact of drought (Szalai et al. 2000; Wilhite et al. 2007; Vicente-Serrano et al. 2012).

At the European scale, research on drought has been particularly focused on the Iberian Peninsula, Mediterranean, and Balkans, which are regions mostly prone to severe drought with impacts on agriculture, water recourses, and ecosystems (Estrela et al. 2000; Livada and Assimakopoulos 2007; Koleva and Alexandrov 2008; Cindrić et al. 2010; Vicente-Serrano et al. 2011). During the last two decades, both droughts and floods in central Europe have increased public awareness of the severity of extreme meteorological events and their environmental and social–economic impacts (e.g. Szalai et al. 2000; Dubrovsky et al. 2008; Brázdil et al. 2009; Trnka et al. 2009a, b; Potop et al. 2010, 2012a, b). According to Dubrovsky et al. (2008), the projected increases in temperature in central Europe along with a slight gain in precipitation amounts during both winter and spring months (associated with decreases in precipitation in summer months) are very likely to increase the frequency of drought occurrence and its severity in central Europe and to enhance the impacts associated with these events.

At the global scale, the recent drought studies of Dai (2011b) and Vicente-Serrano et al. (2011) suggested that the increasing drying trends detected in the global dataset of the Palmer Drought Severity Index (PDSI) and Standardised Precipitation Evapotranspiration Index (SPEI) over many land areas are mainly due to the increasing temperature trend (via evapotranspiration processes) since the mid-1980s. Trenberth (2011) indicated a direct influence of global warming on precipitation. Increased heating leads to greater evaporation and surface drying, thereby increasing the intensity and duration of drought. The models project that patterns of precipitation will not change much and will result in dry areas becoming drier (generally throughout the subtropics) and wet areas becoming wetter, particularly in the mid- to high latitudes. In addition, global warming is leading to an increased risk of heat waves associated with drought. Once soil moisture is depleted, this heating will further contribute to temperature increases and plant wilting.

The 2003 heat wave that affected much of Europe from June to September bears a close resemblance to what many regional climate models are projecting for summers in the latter part of the twenty-first century (Beniston 2004). It was the warmest summer since observations began, and only a few summers have been drier since continuous and reliable precipitation records started. The heat and drought conditions impacted river flows, the power market, and central European glaciers (Fink et al. 2004) and exceptionally increased the incidence of wild fires (Trigo et al. 2006). The 2007 European heat wave during June–August affected mostly south-eastern Europe, with record-breaking temperatures and unprecedented conditions, even for regions accustomed to conditions of extreme heat (Busuioc et al. 2007; Corobov et al. 2010). The summer of 2010 was exceptionally warm in eastern Europe and large parts of Russia, which caused adverse impacts that exceeded in amplitude and spatial extent the previous hottest summer of 2003. The "mega-heat waves" of the 2003 and 2010 events likely broke the 500-year-long seasonal temperature records over approximately 50 % of Europe (Barriopedro et al. 2011). These major heat waves, which affected much of Europe during the last decade, rank among the most severe, both in intensity and duration, during the instrumental period.

In such an atmospheric context, a new concept of drought has been introduced, the "flash drought" (Senay et al. 2008), which has been defined as a severe, short-term event characterised by moisture deficit and abnormally high temperature. A flash drought is the result of a synoptic meteorological pattern in which the reference level of evapotranspiration greatly exceeds the level of precipitation for a period no shorter than 3 weeks during which the Soil Moisture Index (a new drought index recently tested in the Czech Republic) is lower than −5 (Možný et al. 2012).

In previous studies on drought in the Czech Republic (Potop and Možný 2011a, b; Potop and Soukup 2011; Potop et al. 2011, 2012a, b), the Standardised Precipitation Index (SPI) and the SPEI were analysed. The SPEI takes into considerations the role of antecedent conditions in quantifying drought severity. A decadal trend in drought extent was detected by the SPEI in the Czech Republic. More drought episodes were observed during the 1940s, early 1950s, and the 1990s and fewer during the 1910s, 1930s, and 1980s. These drought episodes in the Czech Republic coincide with the secular drought evolution reported for central Europe (Lloyd-Hughes and Saunders 2002; Brázdil et al. 2009). The comparison between the SPEI and SPI indicated differences in representing severe drought records during the decades for (1) the lowest summer negative temperature anomalies combined with the lowest negative precipitation anomalies (cold and dry; during the first two decades of the twentieth century), (2) the highest summer positive temperature anomalies (at the end of the twentieth century), (3) both high spring positive temperature and precipitation anomalies (warm and wet, at the beginning of the twentieth century), and (4) the highest deficits of water balance (1947, 2003, 1994, 1983, and 1933, sorted by the highest deficit) (Potop et al. 2012a, b). Similarities in drought detection with the SPI and SPEI were reported during the decades displaying (1) high positive temperature anomalies in spring associated with below-normal precipitation (warm and dry, during the 1950s, 1990s, and 2000s) and (2) extremely long sunshine duration (155 % of the normal sunshine duration reported for the extremely dry June 2006 and August 2003, up to twice as long as the normal sunshine duration for April 2007 and 2009) associated with a large number of consecutive dry days. It was apparent that temperature played a driving role in summer drought episodes. The positive temperature anomalies contributed to a higher water demand due to increased potential evapotranspiration (PET) at the end of the last century.

The present study aimed to provide a comprehensive analysis of the Czech Republic drought characteristics as quantified with the SPEI for various time lags during the growing season (April–September) during the period 1961–2010.

The paper is organised as follows. The data and methodology are described in Section 2. In Section 3, the results are presented and discussed. This section is organised in the following subsections: 3.1, 3.2, 3.3, 3.4, 3.5, and 3.6 for temporal evolution and persistence of drought, the frequency distribution, temporal extent, spatial extent, trend analysis, and principal modes of SPEI variability, respectively. The summary and conclusions are presented in Section 4.

2 Data and methods

2.1 The SPEI as a multi-scalar drought indicator

To monitor and quantify drought, various indices have been developed, but a unique and universally accepted drought indicator does not exist (Heim 2002; Dai 2011a). A large number of studies related to drought analysis and monitoring have been conducted using either (1) the SPI (McKee et al.

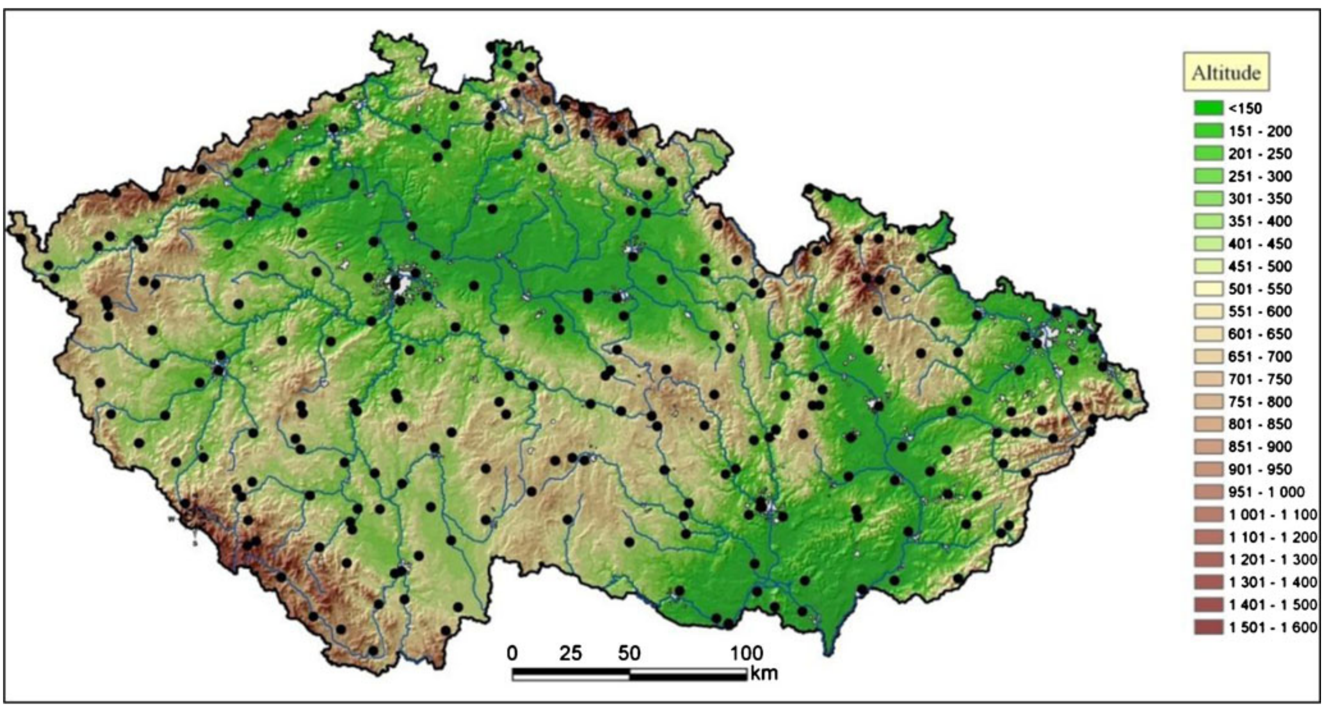


Fig. 1 Location of stations used for the calculation of the SPEI drought index in the Czech Republic

1993), based on a precipitation probabilistic approach or (2) the PDSI (Palmer 1965), based on a soil–water balance equation. Mavromatis (2007) and van der Schrier et al. (2011) obtained similar results for the PDSI using either a simple or complex method to calculate the PET as an input parameter for calculating the PDSI.

A multi-scaling drought indicator is needed to take into account deficits that affect different usable water sources and to distinguish between different types of drought. The newly developed SPEI (Vicente-Serrano et al. 2010) is based on monthly precipitation totals and temperature means and follows a simple approach to calculate the PET based on a normalisation of the simple water balance (Thornthwaite 1948). In developing the SPEI, Vicente-Serrano et al. (2010) followed the same conceptual approach that McKee et al. (1993) devised to develop the SPI. Mathematically, the SPEI is similar to the SPI, but it includes the role of temperature. Because the SPEI is based on a water balance, it can be compared with the self-calibrated PDSI (Wells et al. 2004), as demonstrated with global datasets from observatories located in different climatic zones (Vicente-Serrano et al. 2010). The SPEI combines the sensitivity of the PDSI to changes in evaporative demand (related to temperature fluctuations and trends) with the multi-temporal nature of the SPI.

Another advantage of the SPEI is its independence with respect to the method used to calculate the PET. This independence was demonstrated in previous studies (Potop 2011; Potop et al. 2011b, 2012a, b) when the effect of two different parameterisations of PET for calculating water balance were tested. The first parameterisation was derived from the daily precipitation, saturation vapour pressure, vapour pressure, the vapour pressure deficit, and air temperature mean at 14:00 local time (AMBAV model; Löpemier 1994). The second parameterisation was based on the minimum and maximum air temperature and extra-terrestrial radiation (Hargreaves model; Hargreaves and Samani 1985). The two parameterisations yielded similar SPEI values.

Various lags that might be considered for the SPEI calculation can be related to different drought types in a region. Short lag time scales display a strong relationship with variations in soil moisture that determine water availability for vegetation and agriculture, whereas water resources in reservoirs are mostly related to longer time scales (Dai 2011b; Beguería et al. 2010; Vicente-Serrano et al. 2011). The SPEI is particularly suited for detecting, monitoring, and assessing the effects of global warming on drought conditions.

2.2 Station data

In this study, the SPEI was calculated from monthly records of temperature means and precipitation totals during the period 1961–2010, using a dense network of 184 climatological stations uniformly covering the territory of the Czech Republic. The station elevations range between 158 and 1,490 m above sea level (Fig. 1). The selected stations represent different climate conditions in both lowland and highland regions and reflect differences in the maritime and continental weather regimes that are present across the Czech Republic. Based on the station altitude, three regions were defined: region I groups 89 stations with altitudes below 400 m; region II groups 73 stations with altitudes between 401 and 700 m; and region III groups 22 stations with altitudes above 700 m. This regionalisation has been previously used in other climatic studies in the Czech Republic (Quitt 1971; Tolasz 2007; Trnka et al. 2009b) and corresponds to different land-use types with mostly intensive agriculture, less-intensive agriculture, and forested with limited agricultural production, respectively. Monthly series of temperature and precipitation were selected from the Czech Hydrometeorological Institute CLIDATA database based on the spatial distribution and completeness of time series.

2.3 Quality control and homogenisation

Quality control of the data was conducted by combining several methods: (1) an analysis of the series of differences between the candidate and neighbouring stations (i.e. pairwise comparisons) and (2) applying limits derived from interquartile ranges.

Neighbouring stations (method 1) or reference series (method 2) were selected either by means of correlation or distance scores. Correlation coefficients were applied either to the raw series or to series of first differences (Peterson 1998). In our case, for comparison with neighbouring stations, up to eight nearest stations were selected with a distance limit of 300 km, with altitude difference restricted to 500 m and significant correlation coefficients (Štěpánek et al. 2009).

The relative homogeneity tests applied were as follows: the Standard Normal Homogeneity Test developed by Alexandersson (1986, 1995), the Maronna and Yohai bivariate test (Potter 1981), and the Easterling and Peterson (1995) test. The reference series were calculated as a weighted average from the five nearest stations (with the same period of observations as the candidate series) with statistically significant correlations. The power of weights (inverse distance) was taken as 1 for temperature and as 3 for precipitation. The tests were applied to the monthly temperature means and precipitation totals. All the procedures for quality control and homogenisation were conducted with ProClimDB and AnClim softwares (Štěpánek 2010). More details on quality control and homogenisation procedures are provided Štěpánek et al. (2009).

2.4 The SPEI calculation

For calculating the SPEI, the algorithm developed by Vicente-Serrano et al. (2010) was used. The documentation and executable files are freely available at

Table 1 The seven classes of SPEI categories according to value

SPEI	Drought category	Probability
≥2.0	Extreme wet	0.02
1.50 to 1.99	Severe wet	0.06
1.49 to 1.00	Moderate wet	0.10
0.99 to −0.99	Normal	0.65
−1.00 to −1.49	Moderate drought	0.10
-1.50 to −1.99	Severe drought	0.05
≤−2.00	Extreme drought	0.02

http://digital.csic.es/handle/10261/10002. A batch script was created and used to optimise the calculation of the SPEI for the 184 stations and five accumulation periods: 1, 3, 6, 12, and 24 months. The drought at these time scales is relevant for agriculture (1, 3, and 6 months), hydrology (12 months), and socioeconomic impact (24 months), respectively. The SPEI was calculated for each month of the year, but for this study, only the months of the growing season (April to September) were selected for analysis. A drought episode was defined as a period longer or equal to 1 month during the growing season (April to September) when the SPEI value was less than or equal to −1. The monthly SPEI values of more than −0.99 or less than 0.99 were considered normal conditions. The drought categories according to the SPEI values are presented in Table 1. Drought in the three selected climatic regions was evaluated in greater detail by considering the characteristics of the climatic conditions in the Czech Republic, such as the degree of continentality and the diversity of physico-geographical conditions (topography and soil type).

2.5 Trend analysis

The rank-based non-parametric Mann–Kendall trend test (Mann 1945; Kendall 1975), recommended by the World Meteorological Organisation (Sneyers 1990), was used to detect the SPEI series trends. The Mann–Kendall *Z*-score was used as an indicator of SPEI trends. Compared with parametric tests, the non-parametric Mann–Kendall test is more practical because the data do not need to conform to any particular distribution (Mann 1945; Kendall 1975). Therefore, the Mann–Kendall test can be used in research for trend analysis using monthly and seasonal climatic data. It has been used by many researchers to evaluate the significance of monotonic trends in hydrometeorological time series (Partal and Kahya 2006; Mourato et al. 2010; Longobardi and Villani 2010; Caloiero et al. 2011; Sinoga et al. 2011), including series of drought indices (Rim 2012).

Mann–Kendall statistics are computed as follows. Letting $X_1, X_2, \ldots, X_n$ be a sequence of measurements over time, the null hypothesis (H_0) is that the data come from a population in which the random variables are independent and identically distributed. The alternative hypothesis (H_1) is that the data follow a monotonic trend over time.

Under H_0, the Mann–Kendall test statistic is

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(X_j - X_i\right) \tag{1}$$

$$\text{where } \operatorname{sgn}(\theta) = \begin{cases} +1\ldots\theta > 0 \\ 0\ldots\theta = 0 \\ -1\ldots\theta < 0 \end{cases} \tag{2}$$

Under the hypothesis of independent and randomly distributed random variables, when $n \geq 8$, the S statistic is approximately normally distributed, with zero mean and variance as follows:

$$\sigma^2 = \frac{n(n-1)(2n+5)}{18} \tag{3}$$

As a consequence, the standardised Z statistics follow a normal standardised distribution:

$$Z = \begin{cases} \frac{S-1}{\sigma} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sigma} & \text{if } S < 0 \end{cases} \tag{4}$$

The hypothesis that there is no trend is rejected when the Z value computed by Eq. (4) is greater in absolute value than the critical value Z_α at a chosen level of significance α.

2.6 Modes of SPEI variability

To identify the principal patterns of variability of the SPEI in the Czech Republic, an Empirical Orthogonal Functions (EOF) analysis (Preisendorfer 1988; von Storch 1995) was performed. The EOF technique aims to identify a new set of variables that captures most of the observed variance from data through a linear combination of the original variables, which facilitates the study of the spatial and temporal variability of the time series in a given domain. This method splits the temporal variance of data into orthogonal patterns called empirical eigenvectors. This approach has been widely used to identify the patterns of drought at global (Dai 2011a, b), European (Ionita et al. 2012), or local (Busuioc et al. 2007) scales.

The EOFs were calculated on detrended and standardised anomalies of the 6-month averaged SPEI series (April to September) of 184 stations.

3 Results and discussion

3.1 Temporal evolution and persistence of drought

3.1.1 General aspects

The SPEI associated with a specific time scale is a useful tool for monitoring drought. Different SPEI series were obtained for different time scales representing the cumulative water balance over the previous *n* months. To characterise the temporal evolution of drought during the growing season, the monthly series of the SPEI for the months of April to September were averaged at each station for each SPEI accumulation period (1, 3, 6, 12, and 24 months, respectively). Then, these SPEI time series were averaged over all 184 stations to obtain a time series of the drought index at the country level. To obtain the time series of the drought index characterising each of the three regions, the SPEI time series were averaged over 89, 73, and 22 stations, respectively. It is worth noting that when calculating the SPEI for various accumulation periods longer than 1 month, the moisture characteristic of the lag period is contained in the actual SPEI calculated for the lags of 3 months, 6 months, 12 months, etc. In addition, when averaging the SPEI over the 6 months of the growing season (April to September), the resulting SPEI represents an average characteristic of moisture for these months, also taking into consideration that each monthly SPEI value contains the moisture memory of previous months. As such, the temporal evolution of the SPEI with a 1-month lag represents the year-by-year moisture characteristic of the actual growing season.

In this respect, according to the SPEI values at the country level, during the second half of the twentieth century and the first decade of the twenty-first century, the driest years during

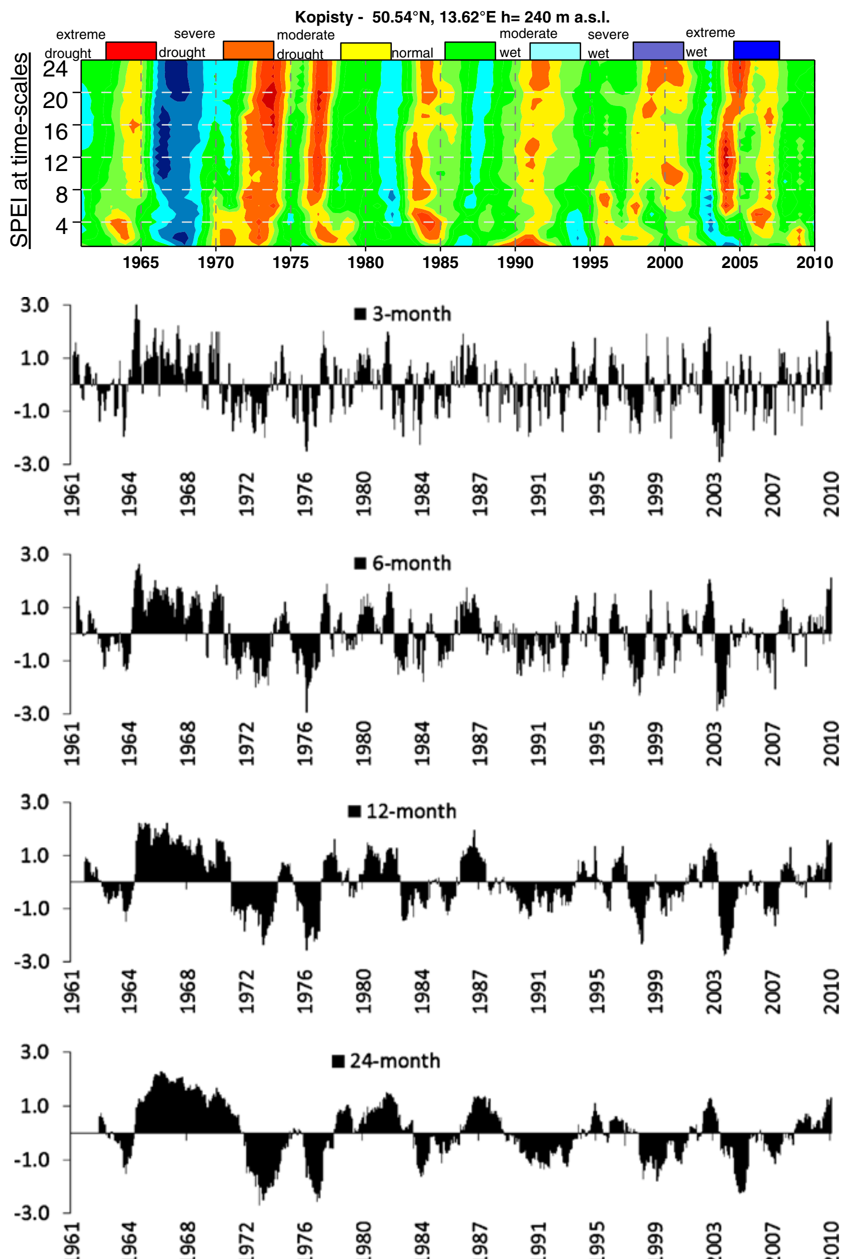


Fig. 2 The evolution of moisture characteristics as quantified by the SPEI indicating the development of drought from 1 to 24 months (12 months × 50 years × 24 SPEI time scales) (*top*) and temporal evolution of the SPEI at 3-, 6-, 12-, and 24-month lags during the growing season (April–September) (*bottom*) at the Kopista climatological station situated in region I (north-west of the Czech Republic)

the growing season were (from most dry to least dry) 2003, 1992, 2000, 1983, 1982, 1976, 2009, and 1999. By contrast, the wettest years during the growing season were 1965, 2010, 1977, 1996, 1966, 2001, 1972, 1980, and 1995. These years have also been identified as extremely dry or extremely wet, respectively, in previous studies of the Czech Republic moisture extremes based on observations at representative stations (Potop et al. 2010). These years appear to be associated with precipitation anomalies in Europe (Brázdil et al. 2009). These results also emphasise that the persistence of lower-than-normal precipitation is the primary cause of drought in central Europe, whereas other meteorological factors, such as temperature, wind, and humidity usually contribute to the intensification of the impact of drought.

The upper panel of Fig. 2 shows an aggregated picture of monthly SPEI at 24 time scales during the period 1961–2010 at Kopisty climatological station, which is situated in region I (altitude lower than 400 m), as an example of the stations situated in the rain shadow of the Ore Mountains chain (the north-western region of the Czech Republic). The picture emphasises the evolution of moisture characteristics as quantified by the SPEI at 1- to 24-month lags. The following lower panels display the temporal evolution of the monthly SPEI at 3-, 6-, 12-, and 24-month lags during the growing season (April to September) at the same station. According to the SPEI values characterising the categories of dry and wet conditions, the periods of drought were 1962–1964, 1971–1974, 1976–1977, 1983–1985, 1991–1992, 1995–2000, and 2003–2007, whereas the periods with wet conditions were 1965–1970, 1978–1982, 1986–1987, and 2001–2002 (Fig. 2).

When averaging over the 6 months of the growing season, either for all stations at the country level or for the selected stations at the regional level, the SPEI values diminish correspondingly. The value of −0.3 (+0.3) was considered the threshold for the averaged SPEI for the 6 months (April to September) at the country level (184 stations) or at the regional level (89, 72, or 22 stations, respectively) to characterise the moderate dry (wet) growing season. This threshold was chosen as a compromise between the seven classes of SPEI categories, according to its value (Table 1) calculated for a single station, and the averaged SPEI series over a number of stations (184, 89, 72, and 22) at the country or regional level, respectively.

At the country level, the numbers of years with SPEI values lower (higher) than this threshold was counted for the averaged SPEI series at various lag periods. The averaged

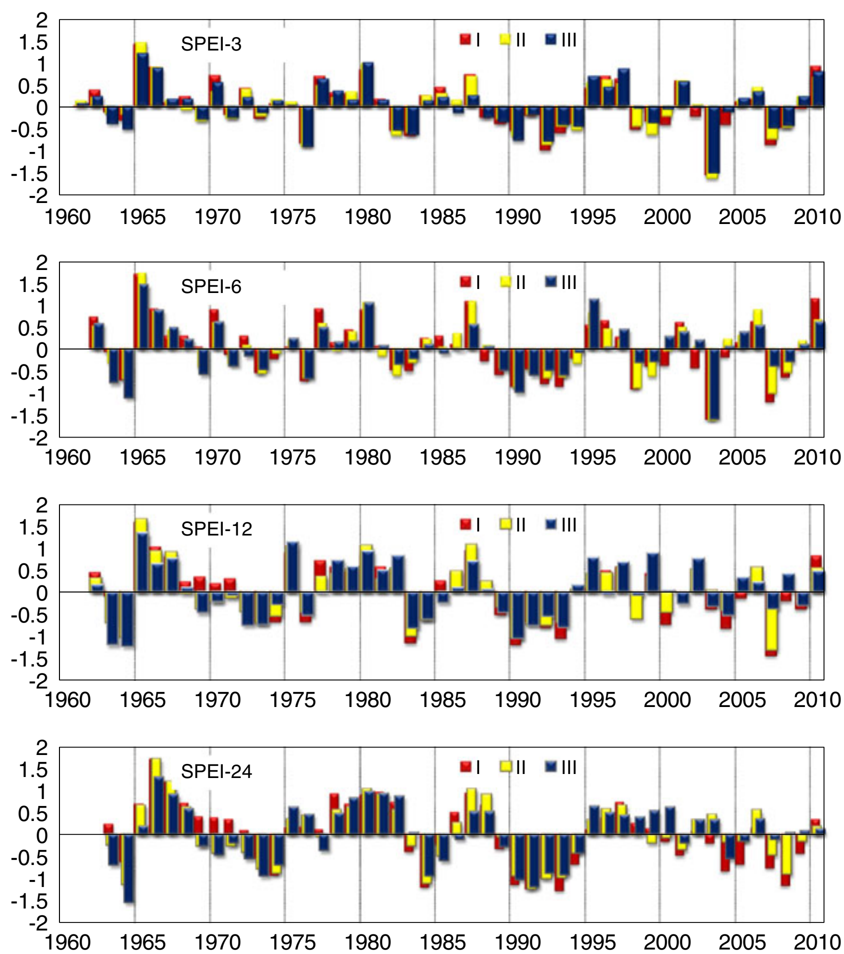


Fig. 3 Temporal evolution of the averaged SPEI over the growing season (April–September) at various lags (3, 6, 12, and 24 months) for the three regions defined by station altitude: regions I (below 400 m), II (between 400 and 700 m), and III (above 700 m)

SPEI for the growing season at a 1-month lag indicates 14 (13) dry (wet) years; at a 3-month lag, 16 (17) dry (wet) years; at a 6-month lag, 19 (16) dry (wet) years; at a 12-month lag, 18 (20) dry (wet) years; and, at a 24-month lag, 17 (17) dry (wet) years, respectively. The differences in these numbers for different SPEI lags may be due to the memory of moisture conditions in previous months. Although the averaged values of the SPEI for the growing season are considerably lower than the individual SPEI value of each month belonging to this season, the exceptionally dry year 2003 is highlighted by the SPEI values for the 3- and 6-month lags. Many monthly SPEI values (April to September) for 2003 were exceptionally dry mainly due to extremely high temperatures during the growing season, which increased evapotranspiration and enhanced drought (Potop et al. 2012a, b). The longest and most intense dry period emphasised by all SPEI series at 3-, 6-, 12- and 24-month lags was 1988–1994. This period is followed, in terms of intensity and duration (SPEI at 12- and 24-month lags), by the periods 1972–1974, 1983–1985, and 2007–2009. By contrast, the wettest periods (SPEI at 12- and 24-month lags) were 1965–1968, 1975–1982, 1986–1988, and 1996–1997.

3.1.2 Regional characteristics

The averaged SPEI series for the three regions delimited on the basis of station altitude were processed in the same manner. The analysis of the regional SPEI series allowed us to highlight the peculiarities of drought characteristics based on station elevations in the Czech Republic. Figure 3 shows the temporal evolution of the averaged SPEI over the six months at the growing season at 3-, 6-, 12-, and 24-month lags for the three regions as defined by station altitude.

No essential difference in drought evolution for these three regions was observed. The year 2003 was the driest and 1965 was the wettest during the growing season, according to the SPEI values calculated at 3- and 6-month lags. The SPEI series at 12- and 24-month lags integrate the moisture characteristics of the preceding months with those of the growing season and highlight the persistence of dry (wet) conditions. The driest growing seasons were during 1972–1974, 1985–1985, and 1989–1994, and the wettest growing seasons were during 1965–1968, 1978–1982, and 1995–1999, respectively.

The number of years with SPEI values lower (higher) than −0.3 (+0.3) was counted for the averaged SPEI series of each region at various lags. Region I (stations with altitudes below 400 m) is characterised by the warmest climate in the country, the highest PET during the growing season, and mostly intensive agriculture. Based on the same selection criteria, the numbers of dry (wet) years according to the averaged SPEI are as follows: 13 (14) dry (wet) years at a 1-month lag, 19 (17) dry (wet) years at a 3-month lag, 18 (19) dry (wet) years at a 6-month lag, 17 (21) dry (wet) years at a 12-month lag, and 17 (19) dry (wet) years at a 24-month lag.

Region II (stations with altitudes between 401 and 700 m) is characterised by a moderate-temperature regime and less-intensive agriculture. The evolution of drought in region II is similar to region I. The number of years with an SPEI value lower (higher) than −0.3 (+0.3) at a 1-month lag was 12 (14), at a 3-month lag was 15 (16), at a 6-month lag was 19 (16), at a 12-month lag was 19 (22), and at a 24-month lag was 19 (20).

Region III (stations with altitude above 700 m) is mostly forested and characterised by limited agricultural production. Figure 3 shows the similarities in drought evolution in region III with those in the previous two regions. However, according to the SPEI values for all lags, particularly during the last decade, the intensity of drought in region III was lower than in regions I and II. The averaged SPEI for region III at a 1-month lag indicates 14 (12) dry (wet) years; at a 3-month lag, 17 (13) dry (wet) years; at a 6-month lag, 17 (15) dry (wet) years; at a 12-month lag, 20 (16) dry (wet) years; and at a 24-month lag, 17 (20) dry (wet) years, respectively.

The highest precipitation amounts usually occur at stations along the border of mountain ranges, which is attributable to the strong effect of the windward location of the stations and to "precipitation-forming" cyclones. Conversely, the lowest precipitation amounts are associated with leeward areas in the foothills of the Ore Mountains (which extend into Central, Western, and Southern Bohemia) and Southern Moravia (Tolasz 2007). Consequently, the windward and leeward effects may bias the expected dependence of dry (wet) growing seasons on station elevation.

3.2 Frequency distribution

In this subsection, drought occurrence is investigated on the basis of the frequency distribution of the SPEI values in seven classes (Table 1). The frequency was calculated as the ratio between the number of occurrences in each SPEI category and the total number of events counted for all stations in a given region and for a given SPEI calculated for various lags (1, 3, 6, 12, and 24 months). The aim was to identify the spatial patterns of frequency distribution of moderate, severe, and extreme droughts (Table 1) over the country for various SPEI lags during the growing season (April–September) based on individual station frequency distribution. The occurrence of these drought categories according to SPEI classes at various lags was also analysed on a regional basis to highlight the drought characteristics of the three climatic regions defined by station altitude as well as on a climatic basis as warm, moderately warm, and cold, respectively. The frequency distribution of the SPEI values was calculated at each station, and the frequency distribution of the three drought categories (moderate, severe, and extreme) was then plotted at the country level (Fig. 4).

In Table 2, the percentage of drought and wet occurrence is expressed in seven classes of moisture categories (in per cent) based on the SPEI series calculated at 1, 3, 6, 12, and 24 months for each individual region for the period 1961–2010. The normal conditions represent between 60.26 and 65.47 % of the total values of the SPEI for all lags in all three regions, whereas moderate drought and moderate wet conditions are almost equally distributed approximately at 10 %. The differences in extremely dry conditions compared with extremely wet conditions increased with increasing SPEI lags; for example, the percentage of extreme drought for the SPEI at a 24-month lag in region I (lowland) was 5.27 %, whereas the percentage of extreme wetness was 1.16 %. The results presented in Table 2 indicate that the occurrence of extremely dry conditions (SPEI value lower than −2.0) tended to prevail over the occurrence of extremely wet conditions (SPEI value higher than +2.0), mostly for the SPEI calculated for longer accumulation periods (12 and 24 months).

The resulting percentages corresponding to moderate, severe, and extreme drought for each station were mapped using the Surfer program. The Surfer program permits the generation of calculated data points (184 station observations) on a regular grid. We used this grid to generate the contour map of the spatial distribution of the frequency of the SPEI values (gridding using the Kriging interpolation technique) for 1-, 3-, 6-, 12-, and 24-month lags (Fig. 4). The spatial interpolation of the SPEI values ranges between longitudes 12.2° and 18.8° E and latitudes 48.6° and 51.0° N. The lowest and highest station altitudes were 158 and 1490 m, respectively.

The left panel of Fig. 4 indicates the spatial distribution of the frequency of moderate drought based on the station percentage of the SPEI values falling into this drought category

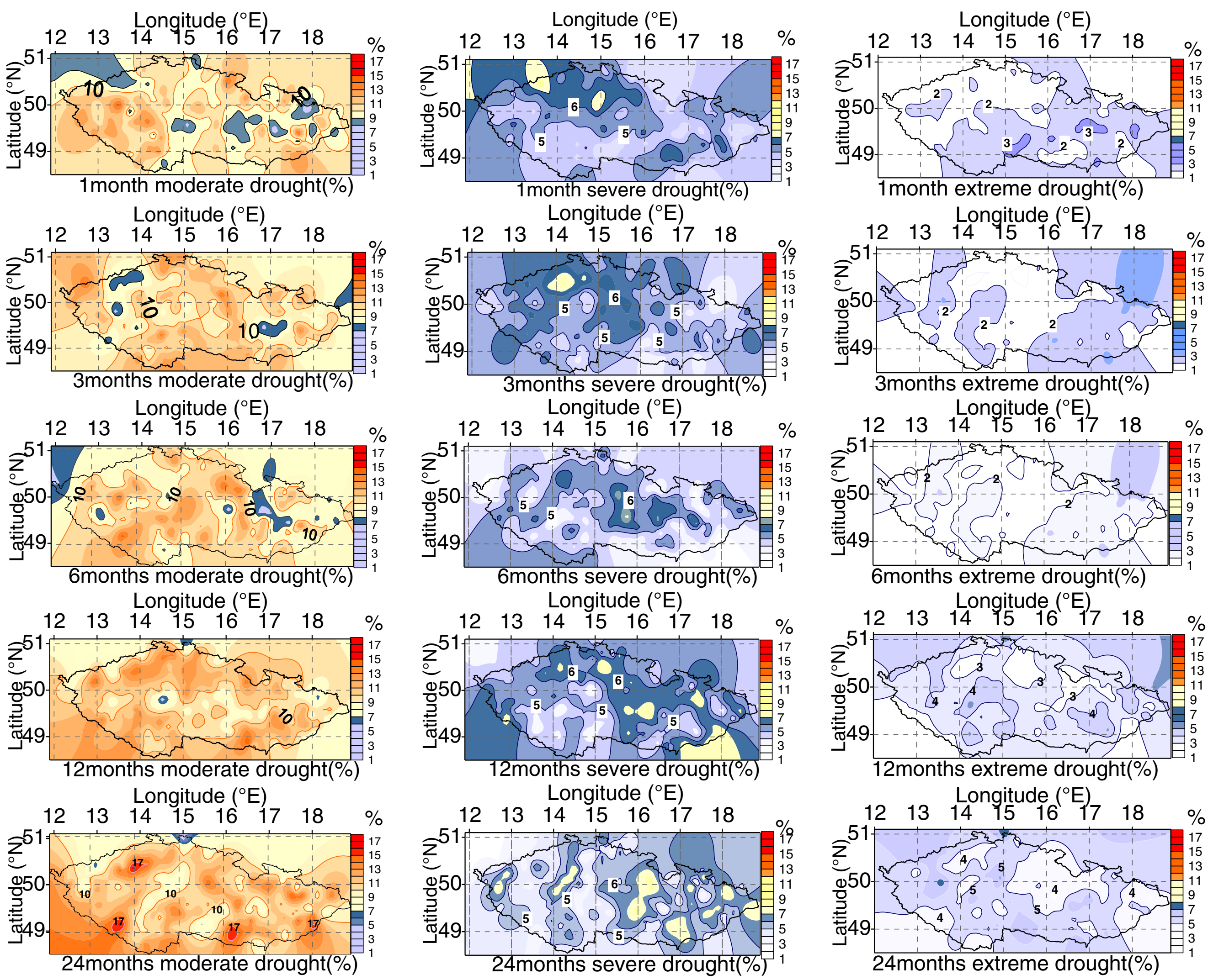


Fig. 4 Spatial distribution of the frequency (in per cent) of the SPEI values falling into the category of moderate (*left*), severe (*middle*), and extreme (*right*) drought based on the station values of the SPEI at various lags (1, 3, 6, 12, and 24 months)

(Table 1) for 1-, 3-, 6-, 12-, and 24-month lags, respectively. The highest percentage of the SPEI values falling into the moderate drought category (15.7 %) during the growing season tended to occur in regions with relatively low precipitation and high PET (region I). These regions are located in the rain shadow of the Ore Mountains chain (north-western), south-eastern, south-western, and in the central part of the Elbe lowland for the SPEI calculated for 1- to 3-month lags. The regions with elevations above 600 m are characterised by the lowest frequency of occurrence of moderate drought (lower than 9 %) for the same lag of the SPEI (left panel of Fig. 4). The moderate drought frequency ranges between 6.7 and 15.7 % for short-term drought. As the lag increases from 6 to 12 months, no major changes are observed for the distribution of maximum frequency (15.3 % for SPEI-12). At a 24-month lag, moderate drought tends to occur more frequently, and its spatial coverage is broader than 60 % of the country´s territory. The frequency of drought occurrence ranges between 4 and 17 %, and the maximum frequency lies in the leeward areas of the chain of Ore Mountains, the Šumava Mountains, as well as in the Bohemian upland region (left panel, bottom map of Fig. 4).

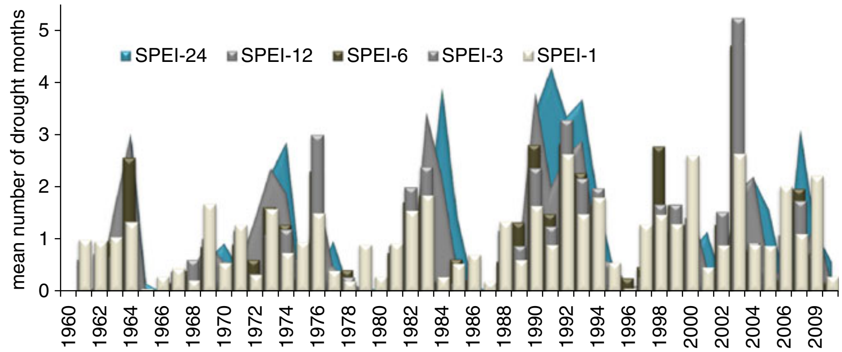
The occurrence of severe drought at short time scales (1 and 3 months) was detected in the regions with the highest drought risk in the Czech Republic. According to the spatial distribution of the frequencies of the SPEI values, the highest occurrence of severe drought (9–10 %) was detected in the following regions: lowlands of the Elbe River valley, central Bohemia, southern Moravia and the lowlands of south-eastern and southern Bohemia. Results similar to those shown in the central panel of Fig. 4 were reported in other studies using drought indices other than the SPEI (Tolasz 2007; Trnka et al. 2009a, b; Potop et al. 2010). The sequence of maps presented in Fig. 4 can also be interpreted as a spatial evolution of drought that develops from short (1 month, meteorological drought) and medium (3 and 6 months, agricultural drought) to long term (12 and 24 months, hydrological drought). The highest percentage of the occurrence of severe meteorological drought (SPEI-01) was recorded in north-western Bohemia and southern Moravia and then extended toward the Elbe lowlands and south-eastern areas with increasing SPEI time scales. The highest frequency of severe drought occurrence ranges between 8.7 and 10.3 %, whereas on average, at the country level, it was 5.5 % for all SPEI lags.

The spatial distribution of the frequency occurrence of extreme drought in the Czech Republic is represented in the right panel of Fig. 4. The areas affected by extreme drought expand gradually as the time scale of the SPEI increases from 1 month (meteorological drought) to 12 and 24 months (hydrological drought). The maps show an increased spatial coverage of extreme drought occurrence at 4 % for the SPEI time scales of 12 and 24 months compared with the same percentage of drought occurrence at shorter time scales. The

Table 2 Frequency distribution (in per cent) of the SPEI values during the growing season (April–September) in seven classes of moisture categories for the SPEI at 1-, 3-, 6-, 12-, and 24-month lags

Region	Extreme drought	Severe drought	Moderate drought	Normal	Moderate wet	Severe wet	Extreme wet
SPEI-1							
I	2.10	5.37	10.13	64.66	10.22	5.59	1.93
II	2.24	4.71	10.53	64.52	10.56	5.61	1.83
III	1.92	5.06	10.20	65.39	10.24	5.26	1.92
SPEI-3							
I	2.17	5.57	9.92	65.15	9.70	5.48	2.01
II	1.94	5.53	10.20	65.19	10.13	4.96	2.05
III	1.62	5.64	10.47	64.91	10.62	4.94	1.80
SPEI-6							
I	2.85	4.83	9.87	64.9	9.96	6.01	1.58
II	2.64	4.86	10.42	64.71	10.24	5.59	1.53
III	2.56	4.39	10.38	65.47	10.08	5.65	1.47
SPEI-12							
I	3.71	5.67	10.33	62.58	10.70	5.54	1.46
II	3.54	5.36	10.30	63.02	10.91	5.49	1.38
III	3.09	5.55	10.35	63.36	11.09	5.61	0.95
SPEI-24							
I	5.27	5.89	11.09	60.26	10.42	5.91	1.16
II	5.18	5.40	11.02	60.53	11.33	5.44	1.10
III	4.98	4.95	10.98	61.92	11.36	5.02	0.77

Fig. 5 The average number of dry months (SPEI≤-1) at various lags (1, 3, 6, 12, and 24 months) for the entire territory of the Czech Republic during the growing season (1961–2010)



highest percentage of extreme drought occurrence is 3.7 % at the short time scale (SPE-1), whereas at longer time scales (SPEI-3 to SPEI-24), the highest percentage of extreme drought increases and ranges between 5.7 and 8.0 %. The stations at an altitude higher than 1,000 m present the lowest percentage of extreme drought occurrence, 0.3 % or lower.

3.3 Temporal extent of drought (SPEI≤-1)

To provide additional insight into the prevalence of drought during the growing season, the duration of drought was calculated. The dry months (SPEI≤-1) were counted for the SPEI series with various lags at each station for each year. Then, these time series of the number of dry months during the growing season at each station were averaged over all 184 stations. Figure 5 represents the temporal evolution of the average number of dry months for the Czech Republic. This graph also depicts the transition of meteorological drought (SPEI-1) toward agricultural (SPEI-3 and SPEI-6) and hydrological (SPEI-12 and SPEI-24) droughts, respectively. For the entire territory of the country, the largest number of dry months (meteorological and agricultural drought) during the growing season was recorded, chronologically, in the following years: 1964, 1976, 1983, 1990, 1992, 1994, 1998, 2000, 2003, and 2007 (Fig. 5). Extreme hydrological drought occurred during the growing seasons of the following years: 1964, 1973, 1974, 1983, 1990, 1992, and 1993. The most persistent hydrological drought was recorded in 1990 when, on average, 3.8 dry months during the growing season were reported at the country level. The most persistent agricultural drought during the growing season was in 2003, when, on average, 5.2 dry months were recorded, followed by the years 1992 (3.3 months) and 1976 (3.0 months). Overall, the mean duration of meteorological drought (SPEI-01) for the period 1961–1989 was 0.8 months; for the period 1990–2010, the average duration of drought was 1.4 months. Moreover, the largest number of dry months was recorded during the last two decades. In addition, 1992, 2000, and 2003 were exceptionally dry years, with an average of 2.6 dry months during the growing season.

Based on the average number of dry months during the growing season counted for SPEI-3 and SPEI-6, the year 2003 ranked at the top, with an average of 5.3 dry months. Furthermore, 2003 ranks as the driest since 1961 in terms of persistence of drought during the growing season at the majority of climatological stations for all SPEI time scales. In addition, 2007 ranks as the second driest and longest growing season in regions I and II, with an average of 3.8 dry months, whereas, in region III, the second driest year was 1964, with an average of 3.5 dry months (data not shown). This comparison indicates that there is not a large difference between regions in terms of the average number of dry months. However, the main difference between the regions is that the overwhelming majority of extreme drought months during the growing seasons in regions I and II were concentrated during the spring months, whereas in region III, the extreme drought months were concentrated during the summer months.

Regarding the longest SPEI time scales (SPEI-12 and SPEI-24), the longest dry growing season, with an average of 4.4 dry months, was 1991 in regions I and II, whereas in region III, 1964 had the longest dry growing season, with an average of 4.9 dry months. The analysis of temporal evolution of hydrological drought indicates that the majority of longest dry growing seasons was recorded in regions I and II during the following years: 1991, 1993, 1984, 1990, 2008, 1992, 1974, and 2007, whereas the hydrological drought of 1973 (3.6 months on average) was detected by the SPEI-24 only in region III (data not shown).

These results indicate that the average number of dry months during the driest growing seasons ranges from 1.5 to 4.6 months as the time scales of the accumulation period for the SPEI increases from 1 to 24 months. These results were observed at the country level during the years 1964, 1990, and 2007, whereas for 2007, these findings were true only in regions I and II. By contrast, the average number of dry months during the driest growing season decreases with increasing SPEI time scale during the following years: 1976, 1983, 1992, 1994, 2000, 2003, and 2009. The most prolonged meteorological drought occurred during 1994, 2000, and 2009. Agricultural drought occurred after meteorological drought but before hydrological drought during the driest growing seasons of 1976, 1983, 1992, and 2003.

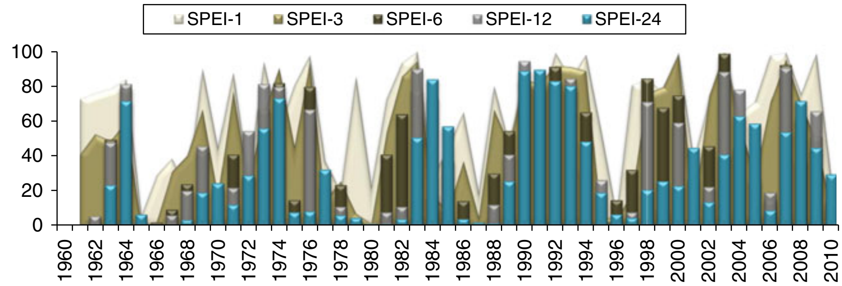


Fig. 6 Percentage of stations (in per cent) for the entire territory of the Czech Republic with an SPEI≤-1 at various lags (1, 3, 6, 12, and 24 months) during the growing season (1961–2010)

According to the SPEI values at longer time scales (SPEI-12 and SPEI-24), the most persistent hydrological droughts were recorded during the periods 1973–1974 and 1990–1994 in all regions.

3.4 Spatial extent

The high density of climatological stations in the Czech Republic used in this study enabled the definition of another

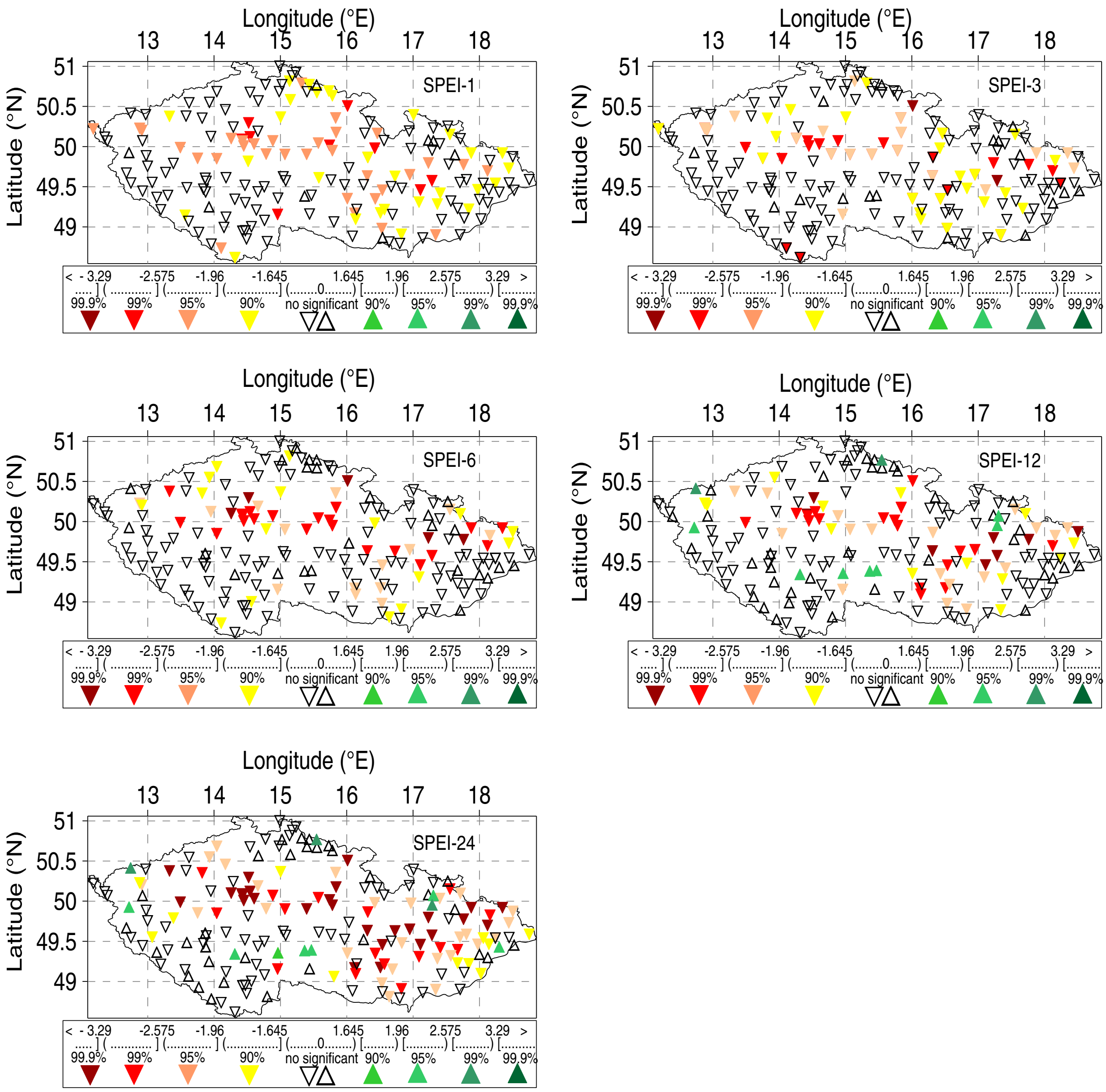


Fig. 7 Mann–Kendall test results for positive and negative trend detection at the 90, 95, 99, and 99.9 % confidence levels (two-tailed test) for the SPEI at 1-, 3-, 6-, 12-, and 24-month lags averaged over the growing season (April–September) at 183 stations

indicator of drought characteristics at the country level, the percentage of stations with an SPEI≤-1 during the growing season. The temporal evolution of the percentage of stations with drought (SPEI≤-1) during the growing season (April-September) at five lags of the SPEI for the entire territory of the Czech Republic is shown in Fig. 6. As the SPEI lags increases (1 to 24 months), this indicator demonstrates that the prevalence of drought at the country level tends to decrease. In many years, the meteorological drought (SPEI-1) had a broad extent at the country level during the growing season, as was the case of in 1983, when drought quantified by SPEI≤-1 was recorded at 100 % of the stations, and during 1992, 2000, 2003, 2007, and 2009, when drought was recorded at 99 % of the stations. These findings are in line with other studies on drought in the Czech Republic (Trnka et al. 2009a; Potop et al. 2010). The most extensive agricultural droughts during the growing season, which were recorded at more than 50 % of the stations, occurred in 25 years according to SPEI-3 and in 19 years according to SPEI-6. The largest extent of agricultural drought for both intervals (SPEI-3 and SPEI-6) was recorded during 2003, when SPEI≤-1 occurred at 99 % of the stations. Long-term droughts (SPEI-12 and SPEI-24) were detected in 17 and 13 years, respectively. The most extensive 2-year hydrological drought was recorded in 1990 and 1991 as a consequence of a deficit of moisture accumulation during the previous years. During the growing season of 1990, the prevalence of drought was high (approximately 85 % of the stations) at all SPEI timescales (Fig. 6). This means that the meteorological drought gradually developed into agricultural and hydrological drought, yielding a significant cumulative socio-economic impact (Vicente-Serrano et al. 2010, 2011, 2012).

During the first decade of the twenty-first century, drought was detected at 98–99 % of the stations during 4 years (2000, 2003, 2007, and 2009). These drought events were mainly recorded during spring months (April–May), a period with increased moisture demand for the growth and development of crops (Potop et al. 2010, 2012a, b). The droughts of April 2007 and 2009 were characterised by insufficient water supply in the soil, very little precipitation (14 % of normal), and positive air temperature anomalies accompanied by longer-than-normal sunshine duration, which resulted in a high amount of PET. From an agronomic perspective, these drought conditions mainly impacted the lowland regions with altitudes below 400 m, which are the regions with profitable vegetable cultivation. The consequences of drought impact on the majority of vegetable species were quantified by the reduction or even total loss of production and poor quality yield, often occurring in cases of only short-term drought. When a dry period occurs during an initial stage of crop development, ripening for market is often delayed, and the yield is reduced (Potop et al. 2012a, b). By contrast, the extremely wet anomalies recorded during the growing season of 2010, which were due to high precipitation amounts and negative temperature anomalies recorded during the summer months (June and August), had a devastating impact on crops of certain species of vegetable. Particularly high losses for cucumber crops were reported (Potop and Soukup 2011; Potop et al. 2012a, b).

3.5 Trend analysis

The standardised Z statistics (Eq. 4) of the non-parametric Mann–Kendal test were calculated for each SPEI at 1-, 3-, 6-, 12-, and 24-month accumulation periods, averaged over 6 months (April to September) and for each of the 184 stations that were included in this study. After the analysis of the results, one station was discarded because it appeared to be an outlier. The null hypothesis that there is no trend was rejected when the standardised Z statistic computed using Eq. (4) was greater in absolute value than the critical value Z at the 90, 95, 99, and 99.9 % confidence levels. Because the SPEI is a multi-scalar drought indicator with values ranging from less than or equal to −2 (extreme drought) to more than or equal to 2 (extreme wet) (Table 1), the two-tailed standard normal distribution was considered for the standardised Z

Table 3 Number of stations with positive and negative trend detections at the 90, 95, 99, and 99.9 % confidence levels (two-tailed test) for the SPEI at 1-, 3-, 6-, 12-, and 24-month lags averaged over the growing season (April–September)

Z	Confidence level	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SPEI-24
≤−3.29	99.9 %	0	2	5	8	27
(−3.29 to −2.575]	99 %	9	14	21	18	15
(−2.575 to −1.96]	95 %	35	18	14	18	26
(−1.96 to −1.645]	90 %	27	23	16	13	11
(−1.645 to 0]	–	104	109	102	81	63
(0 to 1.645)	–	8	17	25	36	31
[1.645 to 1.96	90 %	0	0	0	0	1
[1.96 to 2.575)	95 %	0	0	0	7	7
[2.575 to 3.29)	99 %	0	0	0	2	2
≥3.29	99.9 %	0	0	0	0	0

Table 4 Percentages of explained variance of the leading EOFs of the SPEI at 1-, 3-, 6-, 12-, and 24-month lags averaged over the growing season (April–September)

	Explained variance (%)				
	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SPEI-24
EOF1	66.04	61.82	60.48	57.66	55.56
EOF2	6.86	7.53	8.45	10.28	10.70
EOF3	4.00	5.15	5.23	5.78	6.51

statistics of the Mann–Kendall test. The results of the Mann–Kendall trend test at each station for the SPEI at 1-, 3-, 6-, 12-, and 24-month lags are represented in Fig. 7, and the number of stations where positive or negative trends of the SPEI were detected at 90, 95, 99, and 99.9 % confidence levels is presented in Table 3. For SPEI-1, a negative trend (drought) was detected at 27 stations at the 90 % confidence level, at 35 stations at the 95 % confidence level, and at 9 stations at the 99 % confidence level. Furthermore, a non-significant negative trend was detected at 104 stations for SPEI-1.

The number of stations where a negative trend of the SPEI was detected at high confidence levels (99 and 99.9 %) increases when the accumulation period for the calculation of the SPEI increases. Thus, for SPEI-3, a negative significant trend was detected at 14 stations at the 99 % confidence level and at 2 stations at the 99.9 % confidence level. For SPEI-6, a negative significant trend was detected at 21 stations at the 99 % confidence level and at 5 stations at the 99.9 % confidence level. For SPEI-12, a negative significant trend was detected at 18 stations at a 99 % confidence level and at 8 stations at a 99.9 % confidence level, whereas for SPEI-24, a negative significant trend was detected at 15 stations at a 99 % confidence level and at 27 stations at a 99.9 % confidence level. The results also indicate that a non-significant positive trend is observed at a larger number of stations as the accumulation period for the calculation of the SPEI increases. Concurrently, a significant positive trend was detected at 7 stations at a 95 % confidence level and at 2 stations at a 99 % confidence level for SPEI-12 and SPEI-24, respectively (Table 3). For the spatial distribution of stations with a significant negative trend of the SPEI for all five accumulation periods (1, 3, 6, 12, and 24 months), it is worth noting that these stations are predominantly located in the lowlands, which are regions characterised by intense agriculture (Fig. 7). In these regions, a negative correlation (i.e. damaging effects) was observed between the detrended yield of sugar beets and the SPEI at time scales from 1 to 7 months during the months of May, July, and August (r=−0.37 to −0.55) (Potop and Türkott 2012). In addition, significant negative correlations between the SPEI during the growing season and the detrended yields of root vegetables (r=−0.68) were also reported (Potop et al. 2012a, b).

As the accumulation period for calculation of the SPEI increases (from 1 to 24 months), the persistence of drought in these regions is increasingly significant at high confidence levels (99 and 99.9 %). The majority of the stations where a significant positive trend of the SPEI was detected are located in the highlands (Fig. 7). The thermic and pluviometric regimes of these stations were not significantly affected by the overall increasing temperature trend and decreasing precipitation trends in Europe (Brifa et al. 2009). Other studies (Trnka et al. 2009a; Brázdil et al. 2009) indicate that the number of stations with statistically significant trends towards drier conditions (in terms of available soil moisture) prevail in the Czech Republic over those where either no trend at all or a tendency towards wetter conditions was noted.

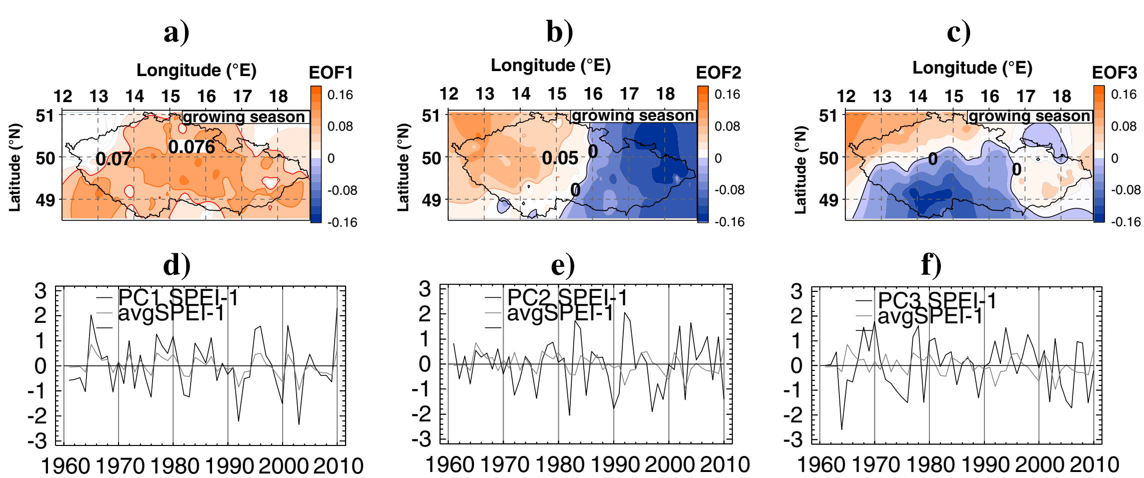


Fig. 8 The spatial distribution of the three leading EOFs of the 1-month lag SPEI averaged over the growing season (April–September) (*top*) and the standardised coefficient time series of the corresponding PCs, together with the spatially averaged series of SPEI-1 (*bottom*)

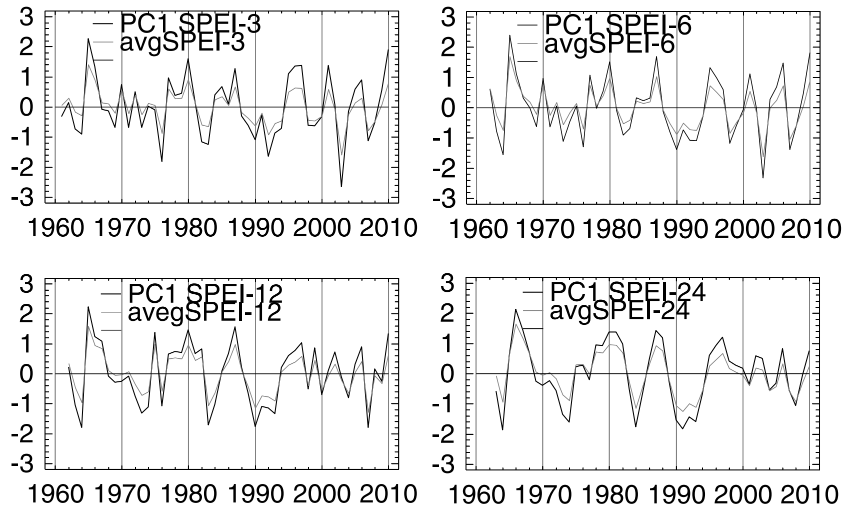


Fig. 9 Standardised coefficient time series of the principal component (PC1) of the SPEI at 3-, 6-, 12-, and 24-month lags averaged over the growing season (April–September), together with the spatially averaged series of the SPEI

Our results indicating an increasing number of stations prone to significant drought trends at increasing time scales are in line with other recent findings (Lloyd-Hughes 2012; Ionita et al. 2012).

3.6 Principal modes of SPEI variability

To identify the dominant pattern of variability of the SPEI during the growing season (April to September), an EOF analysis of the SPEI for five accumulation periods (1, 3, 6, 12, and 24 months) at 184 stations was performed. The explained variance of the EOF1 of the averaged SPEI over the growing season ranges between 66.04 and 55.56 % as the time scale of the accumulation period for the calculation of the SPEI increases from 1 to 24 months (the first row of Table 4). The explained variances of the EOF2 and EOF3 ranges between 6.86 and 10.70 and 4 and 6.51 %, respectively, as the SPEI is calculated for 1- to 24-month lags (the second and the third row of Table 4, respectively). Because the spatial patterns of the three leading EOFs do not differ essentially for various lags in the calculation of the SPEI, only the loading patterns of the SPEI at a 1-month lag are shown, as an example, in Fig. 8. The pattern of EOF1 is presented in Fig. 8a. Its spatial coefficients have the same sign at all stations. These results indicate that the moisture variability quantified by the SPEI is influenced by large-scale factors. The spatial coefficients of EOF2 separate the western and eastern halves of the country's territory (Fig. 8b), whereas the spatial coefficients of EOF3 delimit the southern and northern parts.

Such a regionalisation roughly separates the lowlands and the highlands and corresponds, to some extent, to the regionalisation previously used in other studies (Tolasz 2007; Trnka et al. 2009a, b). In these studies, three climatically homogeneous regions corresponding to the altitudes below 400, between 401 and 700, and above 700 m (Figs. 1 and 8a–c) were identified. Moreover, these regions also correspond to the climatic classification of Quitt (1971), in which three main climatic regions (warm, moderate warm, and cold) were defined based on 14 climatic characteristics.

The corresponding PC1, PC2, and PC3 temporal series of coefficients are represented in Fig. 8d–f, respectively. The representative time series of the spatially averaged SPEI-1 for all 184 stations is superimposed on these graphs. The PC1 temporal series of coefficients displays the same temporal evolution as the spatially averaged series of SPEI-1 identifying the dry and wet years and the intensity of their moisture anomalies. As shown in Fig. 8d, both the magnitudes of the PC1 series of the coefficients and of the averaged SPEI-1 indicate that the year 2003 was the driest during the period 1961–2010. The periods with consecutive dry years were 1975–1976, 1981–1983, 1988–1994, 1998–2000, and 2006–2009. The similarity in the evolution of the PC1 temporal series of coefficients and of the spatially averaged series of SPEI-1, together with the high percentage of variance explained by the EOF1, indicate that large-scale factors are driving the dry and wet conditions at the country level. As for the temporal evolution of PC2 and PC3, the series of coefficients are presented in Fig. 8e, f, respectively, and are only partly in phase with the spatially averaged SPEI-1 for all 184 stations. This is understandable because the patterns of EOF2 and EOF3 represent the regional characteristics of moisture variability quantified by SPEI-1. In addition, the percentages of variance explained by EOF2 and EOF3 are 6.86 and 4 %, respectively, which are much lower than that explained by EOF1. However, some periods with consecutive dry years identified both in the averaged SPEI-1 series and in the PC1 series of coefficients are also captured by the PC2 and PC3 series of coefficients. These are as follows: 1975–1976, 1981–1982, and 1997–2001 for PC2 and 1975–1976 and 2004–2006 for PC3.

Similarly, the PC1 temporal series of coefficients of the SPEI at 3-, 6-, 12-, and 24-month lags were compared with the corresponding spatially averaged series of the SPEI. The graphs represented in Fig. 9 display a good match between these series. The year 2003 appears to be the driest in terms of the magnitude of PC1 and averaged SPEI at 3- and 6-month lags. In addition, the periods with consecutive dry years are almost identical for SPEI-3 and SPEI-6. These are as follows: 1973–1976, 1981–1983, 1988–1994, and 2002–2004. As for SPEI-12 and SPEI-24, due to the increase in the lags taken into consideration in calculating the SPEI, the moisture variability is higher and accordingly modulates the time series behaviour. The temporal evolutions of the PC2 and PC3 series of coefficients for SPEI-3, SPEI-6, SPEI-12, and SPEI-24, as in the case of SPEI-1, only partly fit with the corresponding spatially averaged SPEI series (data not shown).

4 Summary and conclusions

This study investigated the spatiotemporal characteristics of drought in the Czech Republic during the growing season (April to September), as represented by the SPEI calculated with various lags (1, 3, 6, 12, and 24 months). The characteristics of drought were analysed both at the country level (184 stations) and at the regional levels of the three regions defined by station altitude: region I (89 stations with an altitude below 400 m), which is characterised by mostly intensive agriculture; region II (73 stations with altitudes between 401 and 700 m), which is characterised by less intensive agriculture; and region III (22 stations with altitudes above 700 m), which is mostly forested and has limited agricultural production. Our results provide a comprehensive assessment of drought during the growing season in terms of temporal and spatial evolution, regionalisation, frequency distribution, duration, tendency, and patterns of spatial and temporal variability. Most of the results presented in this paper are in line with findings reported in other studies and enhance the knowledge and understanding of drought phenomena in the Czech Republic. The main results are summarised as follows:

- The temporal evolution of the averaged SPEI during the growing season at the country level for various lags (1, 3, 6, 12, and 24 months) highlights the year-by-year moisture characteristics of this season. The longest and most intense dry period was 1988–1994, followed by the periods 1972–1974, 1983–1985, and 2007–2009 (according to the SPEI values at 12- and 24-month lags). The wettest periods were 1965–1968, 1975–1982, 1986–1988, and 1996–1997. These results agree with other studies at the European scale (Lloyd-Hughes 2012; Briffa et al. 2009) and country level (Trnka et al. 2009a, b; Potop et al. 2011), and update the knowledge of drought in the Czech Republic.
- The temporal evolution of the averaged SPEI during the growing season for the three regions delimited by station altitude presents features similar to those identified at the country level. However, the main difference between the regions is that the majority of extreme dry months during the growing seasons in regions I and II were concentrated in spring months, whereas in region III, extreme dry months were concentrated in the summer months. The analysis of the temporal evolution of drought indicates that the majority of the longest dry growing seasons were recorded in regions I and II. As at the country level, the number of dry (wet) growing seasons at the regional level increases as the SPEI lag increases from 1 to 6 months in all three regions and then slightly decreases as the SPEI lag increases from 12 to 24 months.
- The spatial distribution of the frequency SPEI values at various lags indicates that the highest percentage of drought occurrence for SPEI at 1-, 3-, and 6-month lags occurred in the lowlands (region I), which is characterised by low precipitation and high evapotranspiration. Moderate drought ranges between 6.7 and 15.7 %. The occurrence of severe drought at short time scales (1 to 3 months) was detected in the lowlands of the Elbe River valley, central Bohemia, southern Moravia, and the lowlands of southern Bohemia. The frequency of severe drought ranges between 8.7 and 10.3 %. On average, at the country level, the extreme drought ranges between 1.62 (for SPEI at a 3-month lag) and 5.27 % (for SPEI at a 24-month lag), and the highest percentage reaches 8 %. These results enhance the current knowledge of drought in the Czech Republic.
- To provide greater insight into the duration of drought during the growing season, the number of dry months (SPEI≤-1) was counted for each SPEI series with various lags at each station and then averaged at the country and regional level. The year 2003 had the most persistent drought (5.3 months) during the growing season according to the SPEI at lags of 3 and 6 months. The temporal evolution of the percentage of stations with an SPEI≤-1 at various lags was another indicator of drought extension at the country level. These indicate that drought at shorter time scales (1- to 6-month lags) has a greater prevalence than drought at longer time scales (12- and 24-month lags). However, during the period 1990–1993, drought at 12- and 24-month lags exhibited the largest expansion at the country level (approximately 80 % of the stations) during the growing season. The exceptionally hot and dry year of 2003 and other extreme events of the last few decades have been extensively analysed (Beniston 2004; Fink et al. 2004; Trigo et al. 2006; Lloyd-Hughes 2012) both at the European and at the country levels (Brázdil et al. 2009; Barriopedro et al. 2011). Our results

are in line with these findings and provide greater insights into the complexity of these phenomena and their ancillary effects on various systems at the regional scale.

- The results of the non-parametric Mann–Kendall trend test applied to the SPEI series indicated negative trends (drought) at the majority of the stations. The percentage of stations displaying significant negative trends for the 90, 95, 99, and 99.9 % confidence levels is approximately 40 %. The approach we used has been (Sneyers 1990) extensively applied in other studies to detect trends in temperature and precipitation series (Caloiero et al. 2011; Coroborov et al. 2010; Longobardi and Villani 2010; Partal and Kahya 2006) and also for drought index series (Dai 2011b; Lloyd-Hughes and Saunders 2002; Rim 2012). Our results complete the knowledge of drought trends in the Czech Republic.
- The EOF analysis of the SPEI at 1-, 3-, 6-, 12-, and 24-month lags during the growing season identified patterns of spatial and temporal variability. These results update the knowledge on drought variability at the country level. The patterns of the three leading EOFs of the SPEI at various lags do not display essential differences. The explained variance of EOF1 of the SPEI at various lags ranges between 66 and 56 % as the time scale of the SPEI lag increases from 1 to 24 months. These results indicate that large-scale factors drive the drought conditions in the Czech Republic. Our results are in line with other studies in Europe (Ionita et al. 2012). EOF2 and EOF3 explain between 7 and 11 and 4 and 7 % of the variance, respectively, when the SPEI lag increases from 1 to 24 months. The spatial patterns of EOF2 and EOF3 for all time scales of the SPEI correspond to some extent to the regionalisation based on station altitude used in this and previous studies (Tolasz 2007; Trnka et al. 2009b).

The approach to drought characterisation based on the SPEI calculated for various accumulation periods applied to a dense network of climatological stations for the period 1961–2010, provides comprehensive results on the complexity of drought phenomena in the Czech Republic. The results emphasise that drought in the Czech Republic is part of a larger-scale phenomenon but still possesses regional characteristics, most of which being also reported in other studies or identified in the present study. Also, the SPEI suitability for the detection, monitoring, and assessment of drought conditions both at the local and regional scale is worth mentioning.

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