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THE APPLICATION A NEW DROUGHT INDEX - STANDARDIZED PRECIPITATION EVAPOTRANSPIRATION INDEX IN THE CZECH REPUBLIC

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In the present paper, the main aim is to use of the new multi-scalar drought index, standardized precipitation evapotranspiration index (SPEI) while discussing its potential use in studying the evolution of drought severity in the Czech Republic. In quantifying the SPEI is based on the following steps: i) to calculate potential evapotranspiration (ETo); ii) the accumulation of deficit and or surplus a climate water balance at different time scales (P-ETo); and iii) a normalization of the water balance into a Log-logistic probability distribution to obtain the SPEI index series. In order to assess the time evolution of drought conditions in the country, the SPEI and water balance were calculated to shorter (1, 3 and 6 months) and longer (12 and 24 months) timescales. The lower deficit of water balance at 1-month time scales for the all station is July 2006 from -150 to -177 mm. While, the highest surplus of water balance have July 1981, 1997 and August 1977 from 108 to 149 mm. The role of temperature is evident in summer drought episodes, which depend on temperature anomalies (heat waves) that contribute to increasing ETo. SPEI has capacity to detect an intensification of drought severity due to increasing temperature conditions in the decades 1981 and 1990, 1991 and 2000, independent of the analysis timescale. Evolution of drought during the five decades shows its increasing frequency, reinforced by long dry periods in the 1990s and 2000s due to increasing ETo during summer.

Key words: Standardized precipitation evapotranspiration index, drought.

Introduction

Drought is a natural feature of climate variability in all parts of world, even in those having very different hydrological balances. Drought is a phenomenon that is basically linked with a sustained lack of precipitation, and in some case also with excess evapotranspiration. It is difficult to precisely define drought, since meteorological drought results from precipitation deficits, while agricultural drought is identified by total soil moisture deficits, and hydrological drought is related to a shortage of streamflow (Keyantash and Dracup, 2002). Another important feature of drought is their characteristic timescales, which can vary substantially. A single month of deficient rainfall can adversely affect rainfed crops while having virtually no impact on a large reservoir system.

At present, the most advanced drought indices (e.g. the PDSI, SPI and SPEI) take into account the role of antecedent conditions in quantifying drought severity. Moreover, and given the varied response times of different hydrological, agricultural and environmental systems to water availability, the timescale chosen for analyzing drought is important, and some of the most advanced indicators may be calculated for different timescales. Recently, a new drought index, the Standardized Precipitation-Evapotranspiration Index (SPEI), developed by Vicente-Serrano et al. (2010), has been proposed for identifying drought periods. The SPEI is based on a monthly (or weekly) climatic water balance (precipitation minus evapotranspiration), adjusted using a three-parameter log-logistic distribution to take into account common negative values. The values are accumulated to different timescales, following an approach similar to that of the SPI drought index. The evapotranspiration is calculated using the method by Thornthwaite (1948). The SPEI combines the sensitivity of PDSI to changes in evaporation demand (caused by temperature fluctuations and trends) with the simplicity of calculation and multi-temporal nature of the SPI. Among the significant advantages of the SPEI is that it can, like the SPI, be calculated for different timescales to monitor droughts with respect to severity, duration, onset, extent and end. The SPEI's main advantage over other widely used drought indices lies in its ability to identify the role of evapotranspiration and temperature variability on drought assessment in the context of global warming. This fact is demonstrated on the basis of metadata from 11 observatories located in different climatic zones in the world (Vicente-Serrano et al. 2010).

This article is an initial step to application of the new multi-scalar SPEI drought index in studying the evolution of drought severity in the Czech Republic.

Materials and methods

The method of computing the SPEI may be found extensively described in Vicente-Serrano et al. (2010). Nevertheless, for the sake of completeness, we will describe here the main steps for its computation. In this study, in quantifying the SPEI is based on the following steps: i) to calculate potential evapotranspiration; ii) the accumulation of deficit and or surplus a climate water balance at different time scales (P-ETo); and iii) a normalization of the water balance into a Log-logistic probability distribution to obtain the SPEI index series. In order to assess the time evolution of drought conditions in the country, the SPEI and water balance were calculated to shorter (1, 3 and 6 months) and longer (12 and 24 months) timescales. The analysis is based on 50 years of monthly mean maximum and minimum temperature, precipitation data derived from four weather stations (Praha Kbely, Čáslav, Semčice and Hradec Králové) which was recorded by the CHMI.

In as much as the main step in quantifying the SPEI is to calculate evapotranspiration, the main obstacle in its implementation is a lack of meteorological inputs regarding solar radiation, temperature, wind speed and relative humidity from the majority of weather stations in the country's network. Detailed analysis of different methods and tools to indirectly estimate evapotranspiration from various meteorological parameters may be found in Allen et al. (1998), Vicente-Serrano et al. (2007, 2010), and Kohut (2003). In the present study, ETo was calculated following the method of Hargreaves (Hargreaves and Samani 1985). It has been demonstrated that the Hargreaves method is the best alternative tool for quantifying evapotranspiration in large-scale of studies where data are missing (see e.g., Droogers and Allen 2002). This method calculates ETo as a function of minimum and maximum air temperature and extraterrestrial radiation. In addition, in places where Penman-Monteith cannot be calculated due to a lack of data (vapour pressure deficit, wind speed or solar radiation) it should consider that empirical methods, such as a calibrated Hargreaves, can be more reliable than Penman-Monteith calculated with estimations of vapour pressure deficit or any other variable. One of the advantages of SPEI is that independently of which method is used to calculate ETo the result is identical. Therefore, this study was conducted while calculating ETo by Hargreaves' method (Hargreaves and Samani 1985), which uses the following equation:

$$\mathrm{ETo} = 0.0023 \cdot Ra \cdot TD^{0.5}(Tm + 17.8) \qquad (1)$$

where ETo is the daily reference evapotranspiration (monthly average). To obtain the total monthly evapotranspiration, the result must be multiplied by the number of days in the month. *TD* is the difference between the maximum and minimum temperatures in °C (monthly averages). *Tm* is the average monthly temperature. *R*a is the water equivalent of the extraterrestrial radiation in mm day^{-1} (1 MJ/m^2/day = 0.408 mm/day) computed according to Allen et al. (1998). *R*a is usually calculated theoretically as a function of latitude and month of the year:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r * [\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)] \qquad (2)$$

where:

R_a	extraterrestrial radiation [MJ m^{-2} den^{-1}],
G_{sc}	solar constant = 0.0820 MJ m^{-2} min^{-1},
d_r	inverse relative distance Earth-Sun
ω_s	sunset hour angle [rad],
φ	latitude [rad],
δ	solar decimation [rad].

The next step a simply monthly water balance was calculated as difference between precipitation (P_i) and evapotrnspiration (ETo_i) according to:

$$D_i = P_i - ETo_i \qquad (3)$$

The probability distribution of cumulative D_i series is aggregated at different time scales, following the same procedure as that for the SPI. The difference $D^k_{i,j}$ in a given month *j* and year *i* depends on the chosen time scales, *k*.

In quantifying the SPEI is needed to used a three parameter distribution, since in two parameter distributions the variable (x) has a lower boundary of zero ($0 > x < \infty$), whereas in three parameter distributions x can take values in the range ($\gamma > x < \infty$, where γ is the parameter of origin of the distribution), consequently, x can have negative values, which are common in *D* series. To model D_i values at different time scales are used the probability density function of a three parameter Log-logistic distribution:

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\left(1+\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right)^{-2} \qquad (4)$$

where α, β and γ are scale, shape and origin parameters, respectively, for *D* values in the range ($\gamma > D < \infty$).

The Log-logistic distribution adopted for standardizing the *D* series for all time scales is given by:

$$F(x) = \left[1+\left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1} \qquad (5)$$

F (x) value is then transformed to a normal variable by means of the following approximation (Abramowitz and Stegun, 1965):

$$SPEI = W - \frac{C_0+C_1W+C_2W^2}{1+d_1+d_2W^2+d_3W^3}. \qquad (6)$$

where C_o, C_1, C_2, d_1, d_2, d_3 are similar constants as for SPI and W is probability-weighted moments:

$W = \sqrt{-2\ln(P)}$. $P \le 0.5$ – the probability of exceeding a determined D value.

The average value of SPEI is 0, and the standard deviation is 1. The SPEI is a standardized variable, and it can therefore be compared with other SPEI values over time and space. For each time scales, each drought event (period in which SPEI is continuously negative and SPEI ≤ -1), can be defined through its duration (time from the beginning to the end), severity (SPEI value for each month following the classification), magnitude (SPEI sum for each month and for the duration of the severity), intensity (magnitude/duration ratio of the event).

Results and discussion

The climate water balance for time scales 1, 3, 6, 12 and 24 months is shown in Tab. 1. Precipitation and/or soil moisture are not enough to characterize a region climatically, but water balance does provide useful information on this topic. The lower deficit of water balance at 1-month time scales for the all station recorded in July 2006 from -150 to -177 mm. While, the highest surplus of water balance have July 1981, 1997 and August 1977 from 108 to 149 mm. A real problem with water resources appears when a year has both SPEI values (SPEI≤-2) characterizing severely droughty episodes and D values below -150 mm. In Polabí field's crops can reach poor harvest when D is generally less than −200 mm in absolute values. When D shows more severe values, e.g. −300 mm, the economical value of vegetable crops is poor.

Table 1 The highest/lowest values of water balance at the time scales 1, 3, 6, 12 and 24 months

time scales	Water balance deficit, P-ETo		Water balance surplus, P-ETo	
	mm	Year	mm	year
		Čáslav		
1 month	-150	July 2006	+149	July 1997
3 months	-374	July 1994	+137	March 2000
6 months	-589	September 1992	+180	January 2003
12 months	-536	April 1993	+78	July 1965
24 months	-941	January 1984	-	-
		Semčice		
1 month	-151	July 1994	+120	August 1977
3 months	-343	August 1967	+190	December 1974
6 months	-484	September 2003	+220	March 1994
12 months	-485	December 2003	+84	May 1967
24 months	-867	December 2004	-	-
		Praha Kbely		
1 month	-152	July 2006	+134	July 1981
3 months	-343	August 2003	+130	December 1974
6 months	-509	September 2003	+177	December 1981
12 months	-574	December 2003	+26	July 1965
24 months	-950	October 1981	-	-
		Hradec Králové		
1 month	-177	July 2006	+108	July 1981
3 months	-398	July 1967	+181	December 1981
6 months	-577	September 2003	+215	March 1981
12 months	-598	December 2003	+119	January 1981
24 months	-1018	December 2004	+182	January 1982

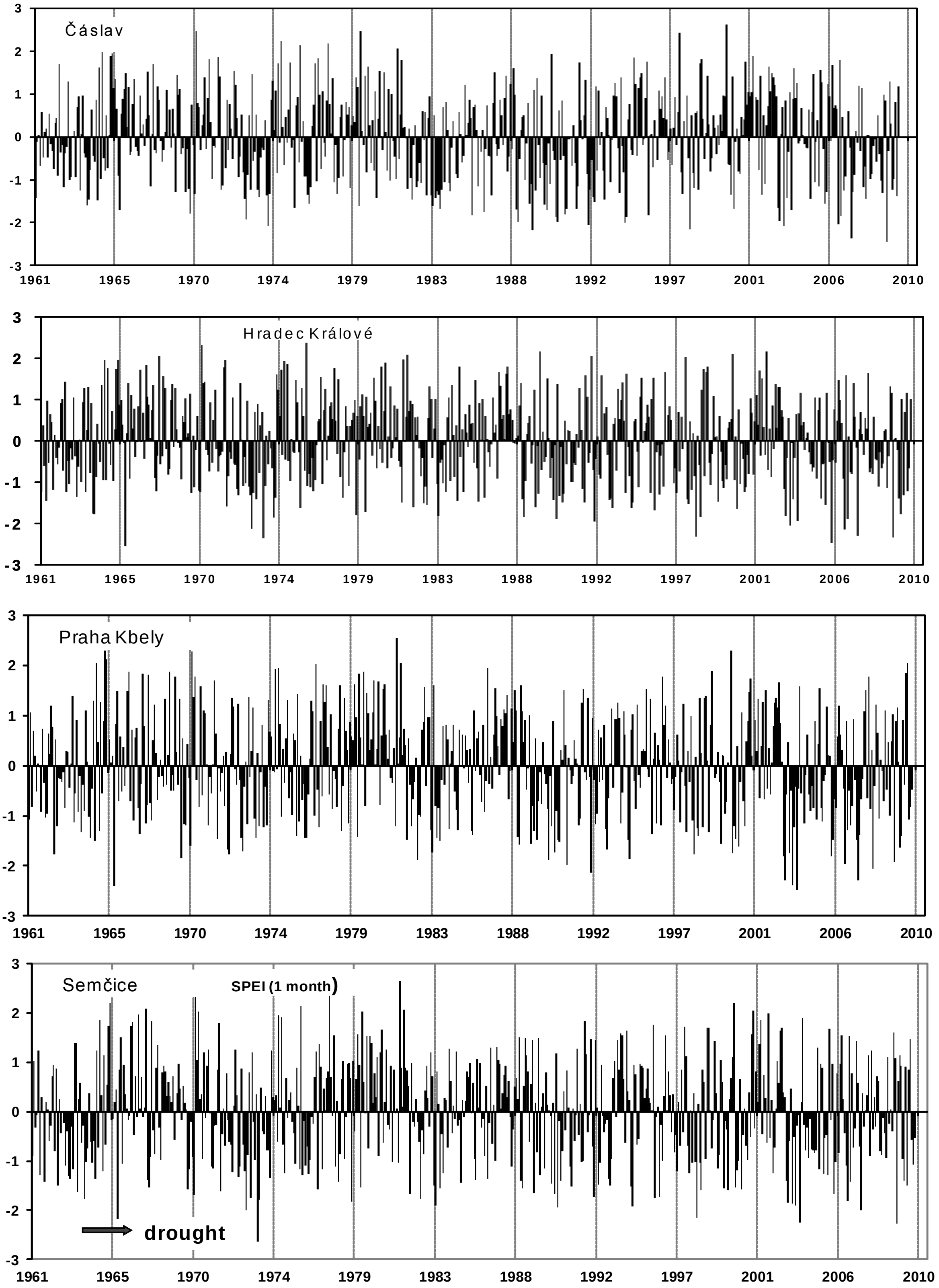

Fig. 1 SPEI series calculated on timescales of 1-month four weather stations (1961–2010)

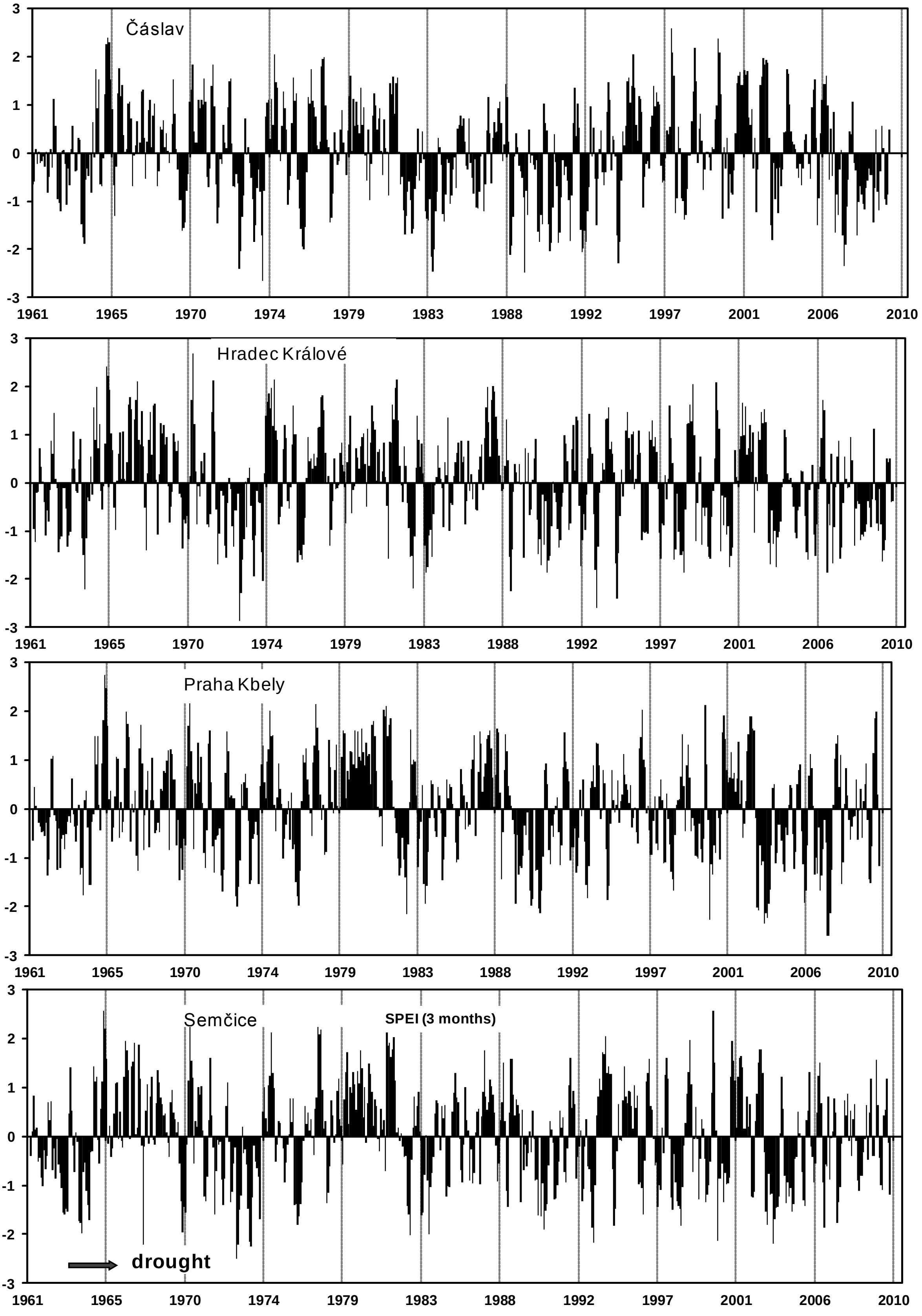

Fig. 2 SPEI series calculated on timescales of 3-month four weather stations (1961–2010)

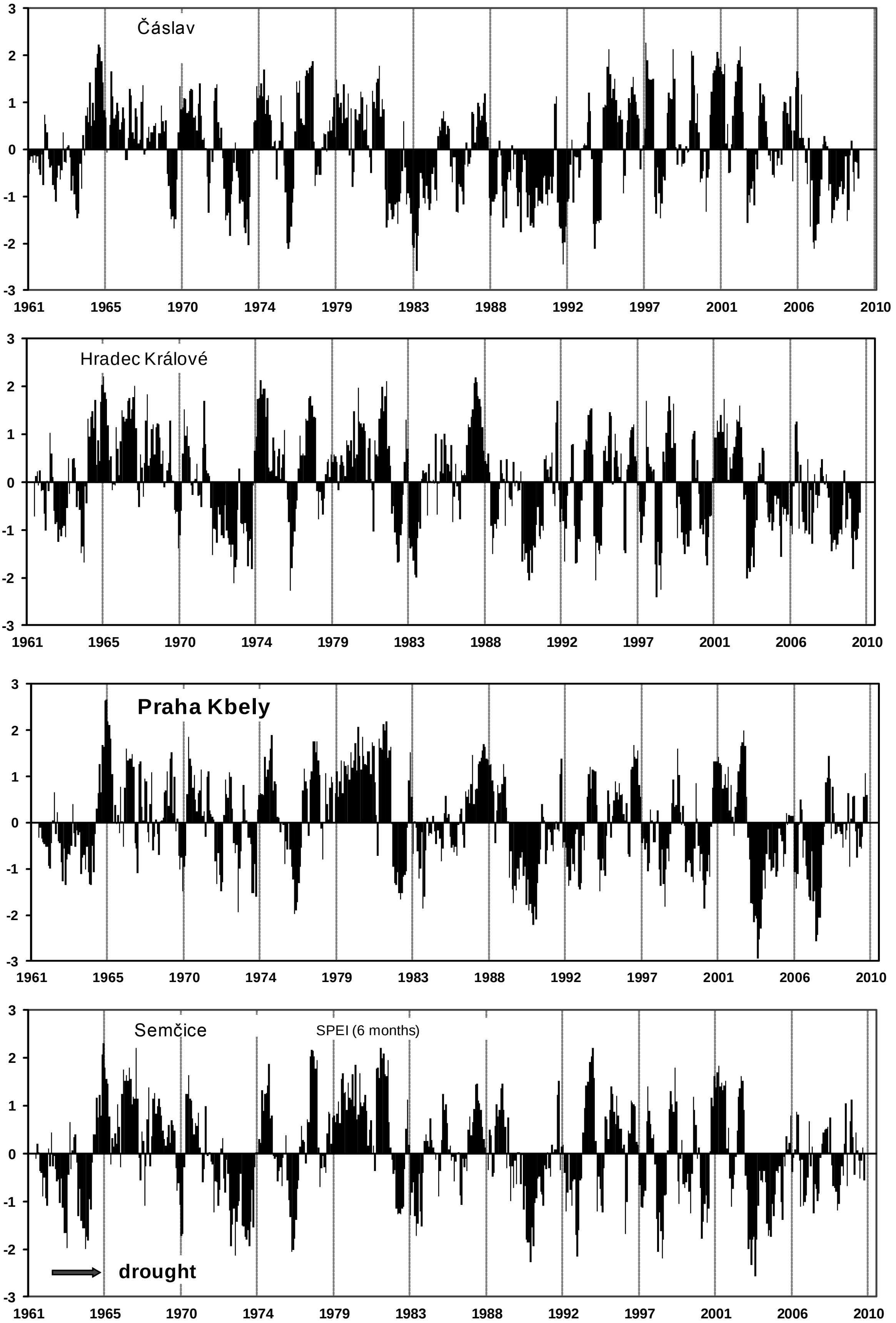

Fig. 3 SPEI series calculated on timescales of 6-month four weather stations (1961–2010)

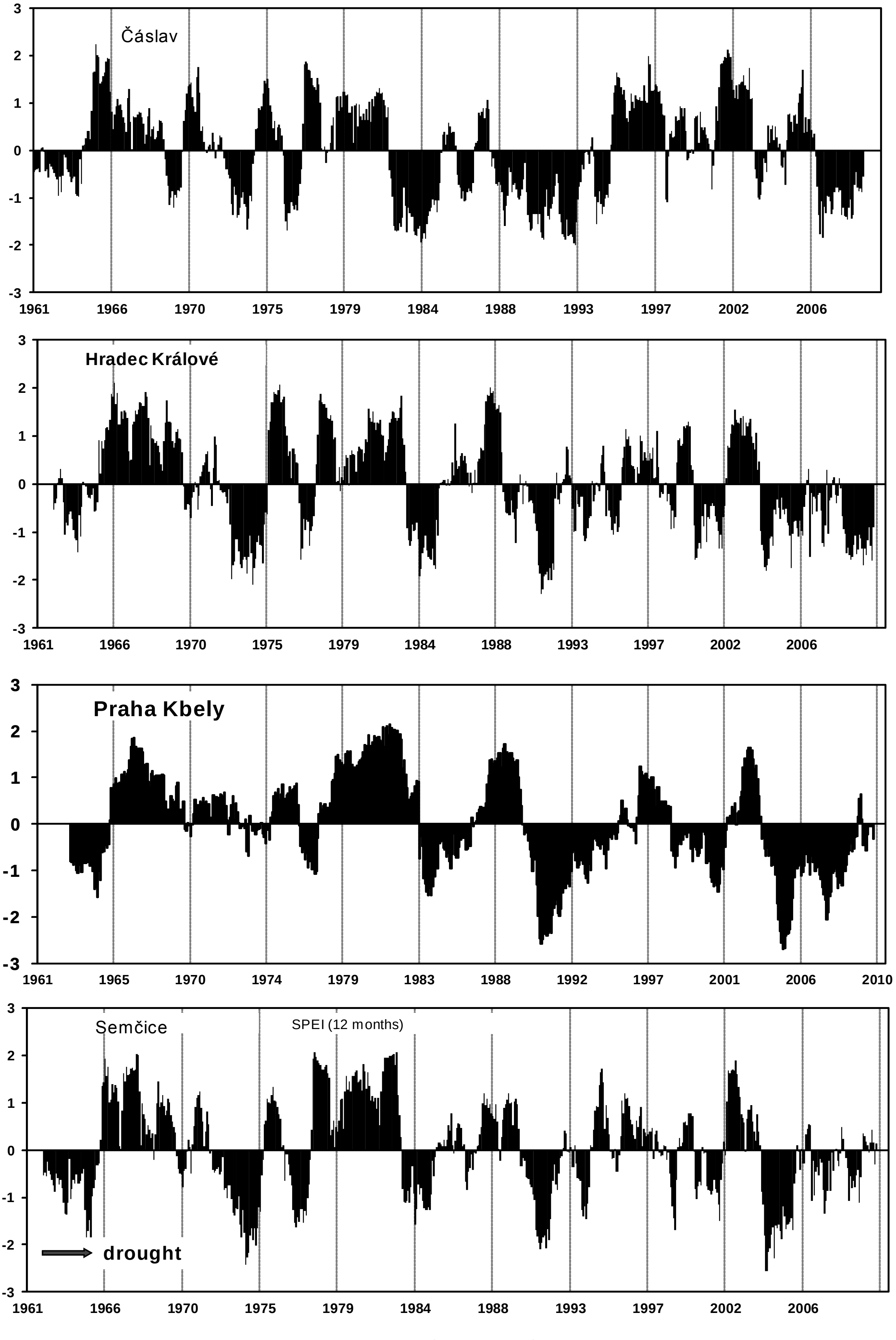

Fig. 4 SPEI series calculated on timescales of 12-month four weather stations (1961–2010)

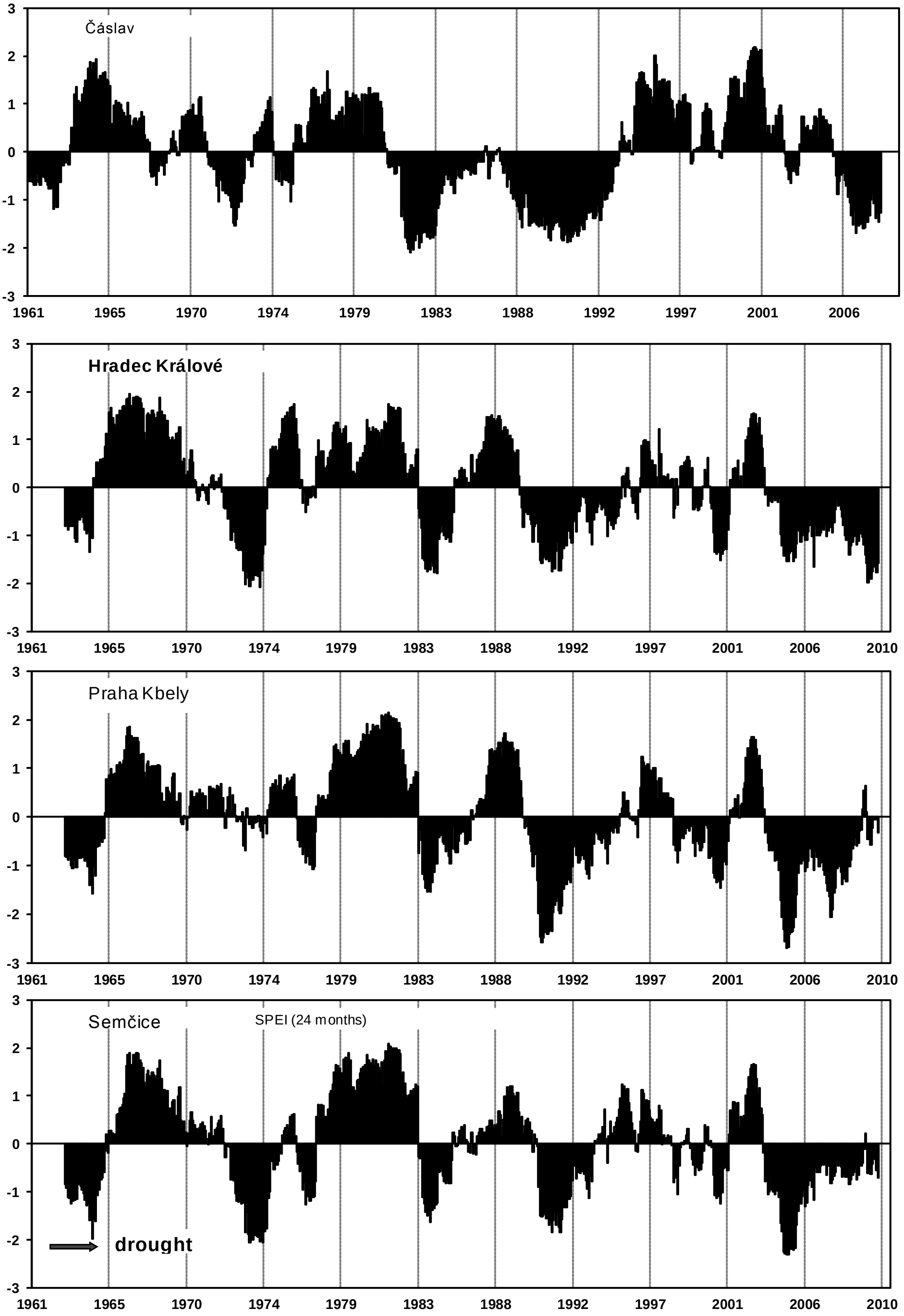

Fig. 5 SPEI series calculated on timescales of 24-month four weather stations (1961–2010)

This section also discusses the evolution of drought severity by different timescales, through a period of 50 years. Temporal drought patterns were studied by series using SPEI drought index. Numerical values of the SPEI were calculated for each of the 4 weather stations, which then allowed us to evaluate the years according to drought severity and duration (Fig. 1-5).

Time series of SPEI was dividing in the five decades (1961-1970, 1971-1980, 1981-1990, 1991-2000 and 2001-2010) and the ***n/m*** ratio was calculated, where "***n***" is the number of consecutive months with SPEI values ≤ -1, and "***m***" is the total number of months of each decades for timescales 1, 3, 6, 12 and 24 months.

The result is illustrated in the Table 2, where shown the frequency of prolonged drought episodes (SPEI values ≤ -1) per decades and whole period of observation. The differences between SPEI values for the four weather stations are small. For Semčice, Praha Kbely and Hradec Králové weather stations the period 1991-2000 ranks as having drought most frequently in all time series, while at Čáslav weather station was 1981-1990. If the average ratio ***n/m*** from whole period of observation for 1-month timescale is 0.18-0.19, then in the period 1991-2000 reach 0.23. For 3-month timescale most frequent drought recorded in decades 1991-2000 and 2001-2010 and its ratio ***n/m*** ranged between 0.16 and 0.27, but in the period of 50-yr is from 0.16 to 0.20. The Table 2 shows that at the longest time scales is the drought periods then longer duration are recorded. In contrast, frequency of drought period decreases with increasing length of time scales. This suggests that at 12 and 24 months timescales the prolonged drought are recorded in the decade 2001-2010. Thereby, the period 2000s also was ranked highest in frequency and intensity by the SPEI drought index. In generally, the SPEI is identifying the most frequent drought episodes in the decades of the 1981s, 1990s and 2000s.

Drought conditions between 1980 and 2000, with minor humid periods are identified by the SPEI at time scales of 12 to 24 months. The SPEI shows an increasing frequency in the period studied and an increasing tendency toward more intensive and prolonged dry episodes.

The role of temperature is evident in summer drought episodes, which depend on temperature anomalies that contribute to increase a higher water demand by ETo at the end of the century. SPEI has capacity to detect an intensification of drought severity due to increasing temperature conditions in the decades 1981 and 1990, 1991 and 2000, independent of the analysis timescale. Evolution of drought during the five decades shows its increasing frequency, reinforced by long dry periods in the 1990s and 2000s. The same result was found in study of Brazdil et al. (2009). According to recent studies (Vicente-Serrano et al., 2010; Potop, 2011) the role of temperature increase on drought conditions was not recognized using the precipitation-based SPI drought index, but was indentified for 2000 drought using the SPEI index.

One should mention that ETo is small during drought, but a small ETo does not always imply drought. Moreover, in humid regions, drought conditions may occur when enhanced ETo is taking place. ETo can be used to measure drought development and it is closely related to vegetation cover. However, it is widely recognized that evapotranspiration determines soil moisture variability, and consequently vegetation water content, which directly affects agricultural droughts commonly recorded using short time scale drought indices. Thus, drought indices that only use evapotranspiration data to monitor agricultural droughts have show better than precipitation-based drought indices. Including the effect of evapotranspiration in explaining the intensification of drought conditions is the most effective climate parameter at mild-latitudes.

Table 3 Comparison of drought frequency by decades (in ratio ***n/m***) as determined using SPEI≤-1.

Drought indices	1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	1961-2010
1-month timescale						
Čáslav	0.11	0.17	0.27	0.17	0.20	0.18
Semčice	0.17	0.20	0.18	0.23	0.16	0.19
Praha Kbely	0.16	0.18	0.19	0.23	0.20	0.19
Hradec Králové	0.13	0.18	0.18	0.23	0.16	0.18
3-months timescale						
Čáslav	0.08	0.14	0.26	0.16	0.16	0.16
Semčice	0.14	0.18	0.15	0.21	0.22	0.19
Praha Kbely	0.10	0.14	0.23	0.17	0.27	0.18
Hradec Králové	0.13	0.17	0.18	0.27	0.25	0.20
6-months timescale						
Čáslav	0.08	0.15	0.34	0.22	0.16	0.19
Semčice	0.15	0.19	0.18	0.20	0.22	0.19
Praha Kbely	0.09	0.12	0.25	0.20	0.25	0.18
Hradec Králové	0.08	0.20	0.22	0.28	0.27	0.20
12-months timescales						
Čáslav	0.03	0.18	0.38	0.28	0.16	0.21
Semčice	0.08	0.27	0.16	0.12	0.25	0.18
Praha Kbely	0.04	0.08	0.21	0.16	0.31	0.16
Hradec Králové	0.04	0.22	0.20	0.14	0.33	0.19
24-months timescales						
Čáslav	0.03	0.08	0.32	0.38	0.17	0.19
Semčice	0.13	0.25	0.13	0.18	0.22	0.18
Praha Kbely	0.06	0.02	0.13	0.22	0.32	0.15
Hradec Králové	0.03	0.19	0.18	0.18	0.39	0.19

The analysis of drought severity clearly shows that the recent period of increased drought severity and duration is unprecedented since 1961. In accordance with the SPEI index, severe drought years were recorded at the 1-month timescale for 1965 (SPEI = - 2.5), 1973, 2003, 2007 and 2009 (SPEI = - 2.4). At 3-months time series the index's greatest negative value registered (Table 3). In anterior studies the same pattern has obtained by SPI and aridity index S_i (Potop, 2008; Potop et al., 2008; Potop et al., 2009, 2010).

Table 3 The highest negative values recorded in SPEI series at shorter (1, 3 and 6 months) and longer (12 and 24 months) timescales.

	Čáslav		**Semčice**		**Praha Kbely**		**Hradec Králové**	
time scales	**SPEI**	**year**	**SPEI**	**year**	**SPEI**	**year**	**SPEI**	**year**
1 month	-2.4	2007, 2009	-2.6	1973	-2.4	2003	-2.5	1965
3 months	-2.7	1974	-2.5	1972	-2.7	2007	-2.9	1972
6 months	-2.6	1984	-2.6	2003	-2.9	2003	-2.4	1998
12 months	-2.0	1993	-2.6	2003	-2.9	2003	-2.3	1990
24 months	-2.1	1984	-2.3	2005	-2.7	2004	-2.1	1974

Conclusions

The main aim of the present study was to describe a methodology for assessing the evolution of drought severity by means of the SPEI drought index. Hence, SPEI is a reasonable multi-scalar index for detecting drought conditions, and including the effect of ETo in explaining the intensification of drought conditions in the Czech Republic. Moreover, the algorithm of SPEI calculations permits use of an alternative empirical equation to compute ETo where data are scarce. From the analysis of the results it was concluded that:

- Consecutive months with SPEI ≤ -1 increase with the increase with the SPEI calculation time scale. This depends on the structure of the index. In fact, for 6-month SPEI even one month of water surplus may cause an increase in the SPEI index, the same water balance for 12-month cannot compensate for scarce precipitation of the remaining months;
- Over the whole observation period, there are some time intervals with dry periods for four weather stations, corresponding to the periods, 1981-1990, 1991-2000 and 2000-2010. In such intervals, the SPEI takes values ≤ -1 for a time greater than 6 months, especially for time scales of 12-month and 24-month.
- From four weather stations the highest number of drought events was recorded at Hradec Králové.

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