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ORIGINAL PAPER

Variability of droughts in the Czech Republic, 1881–2006

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Abstract We analyze droughts in the Czech Republic from 1881–2006 based on the Palmer drought severity index (PDSI) and the Z-index using averaged national temperature and precipitation series for the calculations. The standardized precipitation index (SPI), PDSI and Z-index series show an increasing tendency towards longer and more intensive dry episodes in which, for example, droughts that occurred in the mid-1930s, late 1940s–early 1950s, late 1980s–early 1990s and early 2000s were the most severe. Cycles at periods of 3.4–3.5, 4.2–4.3, 5.0–5.1 and 15.4 years exceeded 95% confidence levels in application of maximum entropy spectral analysis. These are expressed at different intensities throughout the period studied. The occurrence of extremely dry and severely dry months is associated with a higher frequency of anticyclonic situations according to the classification employed by the Czech Hydrometeorological Institute. Principal component analysis documents the importance of the ridge from the Siberian High over Central Europe when extreme and severe droughts in months of the winter half-year are considered in terms of sea-level pressure. In the summer half-year, the ridge of the Azores High over Central Europe is the most important. Drought episodes have a profound effect on national and regional agricultural production, with yields being consistently lower than in normal years, as is documented through the example of spring barley, winter wheat, forage crops on arable land, and hay from meadows. Seasons with pronounced drought during the April–June period (e.g., 1947 and 2000) show the most significant yield decreases. Forests appear to be very vulnerable to long-term drought episodes, as it was the case during the dry years of 1992–1994. This study clearly confirms the statistically significant tendency to more intensive dry episodes in the region, driven by temperature increase and precipitation decrease, which has already been suggested in other studies.

1 Introduction

Droughts may be considered, apart from floods, as the most disastrous natural events in the Czech Republic (see e.g., Brázdil et al. 2005, 2007b). Shortage of water during drought episodes has important consequences for agriculture, forestry, water management, and other human activities, as well as for remaining semi-natural ecosystems.

The term ‘drought’ expresses a negative deviation of water balance from the climatological normal over a given area. Deficiency of precipitation over an extended period of time (several weeks to several years) is the primary cause of drought in Central Europe, while other meteorological elements (such as temperature, wind, and humidity) frequently intensify its impacts. Any realistic definition of drought must be specific with respect to region and application. Four interrelated categories of drought – meteorological, agricultural, hydrological and socio-economic – are usually distinguished, based on time scales and impacts (e.g., Heim 2002). Agricultural drought impacts are mainly associated with time scales in terms of weeks to 6–9 months, while hydrological and socioeconomic impacts usually became apparent after longer time intervals. Individual drought categories and their

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time-scales obviously overlap. The occurrence of meteorological drought, however, precedes the onset of specific impacts, so it is extremely important to understand the regional characteristics of meteorological drought before studying the specific impacts of this phenomenon.

Steadily increasing awareness of the effects of drought has led to a number of regional and large-scale studies (see e.g., Dai et al. 1998, 2004; Szinell et al. 1998; Rebetez 1999; Wilhite 2000; Domonkos et al. 2001; Heim 2002; Lloyd-Hughes and Saunders 2002; Panu and Sharma 2002; Svoboda et al. 2002; Pongrácz et al. 2003; Stefan et al. 2004; Sönmez et al. 2005; van der Schrier et al. 2006, 2007; Blenkinsop and Fowler 2007; Livada and Assimakopoulos 2007; Marsh et al. 2007). The temporal and spatial aspects of drought climatology have also been the subjects of several papers that include the territory of the Czech Republic (see e.g., Možný 2004; Blinka 2005; Dufková and Šťastná 2005; Brázdil et al. 2007b; Dubrovský et al. 2007b; Trnka et al. 2007a). However, a number of problems remain to be addressed.

The current paper concentrates on certain new climatological aspects and on the statistical analysis of the long-term temporal variability of drought over the territory of the Czech Republic in the context of observed climate fluctuations in the period 1881–2006. An overview of information on drought indices and the available data is given, and a general description of climate fluctuations in the Czech Republic follows. Temporal drought patterns are studied, using various indices, in terms of trends and fluctuations, cyclicity and synoptic causes. The results obtained are discussed in broader climatological and European contexts. Finally, several examples of drought impact are presented.

2 Drought indices and data

Several indices may be used for the analysis of drought (for an overview, see e.g., Heim 2002). The Palmer drought severity index (PDSI) and the Z-index (Palmer 1965) were employed in this study. They are among the most comprehensive and widely applied methods for the quantification of droughts all over the world (e.g., Szinell et al. 1998; Lloyd-Hughes and Saunders 2002; Ntale and Gan 2003; Dai et al. 2004; van der Schrier et al. 2007). A comprehensive overview of the calculation procedures required to derive the PDSI and Z-index may be found, for example, in Palmer (1965, 1968), Alley (1984) or van der Schrier et al. (2006, 2007). Both Z-index and PDSI can be used to describe drought climatology (e.g., Tolasz et al. 2007; Trnka et al. 2007a) and the Z-index is also used as a good indicator of agricultural drought (e.g., Quiring and Papakryiakou 2003; Trnka et al. 2007b).

In general, PDSI is based on a supply-and-demand approach to the water-balance equation. It thus incorporates antecedent precipitation, moisture supply, and demand at the surface, as calculated by the Thornthwaite (1948) method. The PDSI applies a two-layer bucket-type model for soil moisture computations and makes three assumptions relating to soil profile characteristics: (1) the water-holding capacity of the surface layer is set at a maximum of 25 mm; (2) the water-holding capacity of the underlying layer has a maximum value dependent on the soil type; and (3) water transfer to or from the lower layer occurs only when the surface layer is full or empty. The PDSI itself may be described as an accumulative departure relative to local mean patterns of atmospheric moisture supply and demand at the surface (Palmer 1965, 1968), and it is thought to represent episodes of prolonged drought as well.

PDSI calculation also includes an intermediate term known as the Palmer moisture anomaly index (Z-index), which is a measure of surface moisture anomaly for a given week/month, without consideration of the antecedent conditions characteristic of PDSI. The Z-index may therefore be employed to track short-term deviations of soil moisture from the normal range and is frequently used to estimate, for example, agricultural droughts, since the Z-index responds relatively quickly to changes in soil moisture (Karl 1986; Quiring and Papakryiakou 2003; Trnka et al. 2007b). Because of its capacity to rank the dryness or wetness of individual months, the Z-index has been used as one of the indicators for short-term drought spells. Dai et al. (2004) have demonstrated that the monthly Z-index and PDSI correlate rather well, during the warm season, with observed soil moisture departures across a number of regions on the northern hemisphere.

In this study, self-calibrated versions of the PDSI and Z-index (scPDSI and scZ-index, respectively) were used (Wells et al. 2004). The scPDSI improves upon the 'traditional' PDSI. Lacking computational resources, Palmer calculated a set of empirical weighting factors used in the PDSI algorithm by averaging the values from only a few locations, mainly from the American Midwest. These averaged values for the weighting factors have become a fixed part of the PDSI computation, regardless of the climate in which it is used. Wells et al. (2004) improve the performance of the PDSI by automating the calculations leading to the weighting factors. These weighting factors are determined for each location, and this makes them uniquely appropriate to only that location. A detailed description on how scPDSI is computed may be found in Wells et al. (2004) and, more concisely, in van der Schrier et al. (2006). As the applied versions of scPDSI and scZ-index assumed all the precipitation fell in the form of the rain, the index values during months with a significant proportion of snow precipitation (i.e., December to February) might not reflect actual changes in soil moisture. However, most of the subsequent analysis was focused on the vegetation season and we believe that the resulting overall effect is relatively small. This claim is supported by the results of van der Schrier et al. (2007) who found relatively a small effect on the overall drying trend when a modification of scPDSI, accounting for snow formation and melting, was used in a region where snow precipitation is much more important than in the Czech Republic.

As well as the scPDSI and scZ-index, the "relative" version of both indices (Dubrovský et al. 2007b) was used in some parts of the study. The relative indices differ from the self-calibrated indices by using two different weather series in a two-step process. In the first step, the model of the drought index is calibrated using the reference weather series, which relates to a certain reference station in order to allow for between-station comparisons. Having calibrated the model, it is then applied to the second series, hereafter called the tested series. The tested series might relate either to a different station (to compare the drought conditions in that station with respect to the reference station) and/or to a different period (to compare drought conditions in that period with respect to the reference period). In analyzing drought impact on crop production in various regions of the Czech Republic, we used the reference series created by aggregating data from a set of 233 climatological stations in the Czech Republic which had been compiled for the study of Tolasz et al. (2007). In this case, the reference series represents a wider spectrum of precipitation-temperature situations, which makes the model applicable to a wider spectrum of climatic conditions and allows comparison of drought intensities in different parts of the country. From now on, we shall denote the two relative drought indices as rZ-index and rPDSI.

As drought episodes in Central Europe are closely associated with precipitation deficits, the standardized precipitation index (SPI) was also calculated alongside the scPDSI and scZ-index series. The SPI is in fact a transformation of a given precipitation total aggregated over a selected period (commonly 1 to 24 months, where the shorter time scales may represent agricultural drought and the longer time scales relate better to hydrological drought) into a standardized normal distribution (http://drought.mssl.ucl.ac.uk/spi.html). In this study we used a 12-month SPI significantly correlated (r=0.78) with the scPDSI series and not influenced by annual distribution of precipitation.

The analysis of droughts in the Czech Republic for the period 1881–2006 is based on following mean monthly series:

a) monthly temperature series for the Czech Republic calculated by the method of arithmetical means from data provided by 174 homogenized meteorological series consisting of at least 30 years of observations in the period 1848–2000 (Štěpánek 2004) and extended to 2006 by the same author; temperature series used for calculation were homogenized using the standard normal homogeneity test (SNHT) by Alexandersson (1986)
b) monthly precipitation series for Bohemia (the western part of the Czech Republic) was originally created by the method of isohyets for the period 1876–1956 (Jílek 1957) and extended later by calculations done by the Czech Hydrometeorological Institute
c) monthly precipitation series for Moravia and Silesia (the eastern part of the Czech Republic), calculated by the method of weighted averaging from data provided by 143 rain-gauge stations for the period 1881–1980 (Brázdil et al. 1985), then extended to 1988 and onwards and completed by calculations done by the Czech Hydrometeorological Institute
d) from precipitation series for Bohemia and Moravia and Silesia (testing of the relative homogeneity of two series using the SNHT by Alexandersson 1986, showed no inhomogeneities) a new mean precipitation series for the whole Czech Republic was calculated by the method of weighted means, where the areas of both parts of the Czech Republic were taken into consideration as weights (66.9 and 33.1%, respectively).

Both mean temperature and precipitation series for the whole Czech Republic were used for further analysis and calculations of drought indices, i.e., 12-month SPI, scZ-index, and scPDSI.

In addition to meteorological data, the crop yields of several widely grown crops in the Czech Republic were used to demonstrate large-scale drought impacts. In the case of spring barley and winter wheat, the yield series for the period 1961–2000 were available for individual districts (i.e., administrative units with areas of approximately 1,000 km^2). The mean national yields of spring barley, winter wheat, forage crops on arable land and hay from permanent grasslands were available for the period 1918–2006 (with the exception of the Second World War period). The district yields were detrended using the average annual yield against year-of-harvest for each crop district. The two driest and two wettest seasons were always excluded from trend calculations. The detrending procedure resulted in values of non-standardized residuals (hereafter referred to as yield deviation), calculated for each district, and used in the subsequent analyses. In the 1918–2006 period, the yield deviations were calculated as a difference between the seasonal yield and 5-year running averages. Detrending was essential to avoid inclusion of intensification and technological advances in agricultural production during the 20th century. The same approach was used (e.g., by Quiring and

Papakryiakou 2003) and tested for the Czech Republic by Trnka et al. (2007b).

Meteorological data were complemented by values of the maximum soil water holding capacity (MSWHC) in the rooting zone (up to 1.5 m deep). This parameter, at a resolution of 1 km^2, was estimated using a combination of digitalized maps of soil types (Tomášek 2000) and detailed soil physics data from 1,073 soil pits collected by the Czech National Soil Survey. For each of the 25 soil types, a mean value of MSWHC was determined as an average of the maximum water-holding capacities of all soil pits of a particular soil type in the database. The MSWHC of the individual soil types ranges from 137 to 302 mm and was determined at each soil pit by the weighted soil-water-holding capacities of individual soil horizons, up to the maximum rooting depth. For the calculation of scPDSI and scZ-index time series (1881–2006), a spatial average of MSWHC representing whole territory of the Czech Republic was used (i.e., 182 mm).

3 Climate fluctuations in the Czech Republic

Climate fluctuations in the Czech Republic have been evaluated in several papers taking into consideration either meteorological data since 1961 (e.g., Brázdil et al. 2001, 2007a; Huth and Pokorná 2004, 2005; Moliba et al. 2006; Chládová et al. 2007) or long-term series (see e.g., Pišoft et al. 2004; Štěpánek 2004; Brázdil et al. 2007b).

Series of annual air temperatures in the Czech Republic show a clear rising trend over the period 1881–2006, with a statistically significant linear trend of 0.082°C/10 years (Fig. 1a). This is consistent with the global temperature rise, which has reached a value of 0.74°C over the past 100 years (1906–2005) (IPCC 2007). Annual precipitation totals exhibit a statistically insignificant negative trend of −2.34 mm/10 years (Fig. 1b).

These observed fluctuations in temperature and precipitation, as well as the process of global warming, raise the question as to what extent climate continentality has changed in the Czech Republic. Two indices have been chosen for further processing from among the several available:

(a) The index of temperature continentality K_T, after Gorczyński (1920) is calculated from the formula

$$K_T = (1.7/sin\varphi)(A - 12\sin\varphi)$$

in which A is the annual temperature range (mean monthly maximum minus mean monthly minimum) and φ is the latitude of the given station.

(b) The index of precipitation seasonality, after Markham (1970), which is calculated as the vector sum of the individual monthly totals with the size of the resulting vector then divided by the annual precipitation sum and expressed as a percentage (a lower value of the index marks a more balanced annual variation of precipitation, and *vice versa* – for more details see Brázdil 1978).

In terms of temperature continentality in the Czech Republic (Fig. 1c), there are no significant changes over the period 1881–2006, despite year-by-year fluctuations (maximum value in 1929 with an extremely cold February, minimum in 1974 with very mild winter months). On the other hand, the index of precipitation seasonality shows a clear negative linear trend but its value, at −0.4% per 10 years, is not statistically significant for the significance level of $\alpha = 0.05$ (Fig. 1d). This indicates a long-term tendency towards a more balanced distribution of precipitation over the course of the year.

4 Long-term variability of droughts in the Czech Republic

4.1 Fluctuations of drought in the Czech Republic

Long-term fluctuations of 12-month SPI, scZ-index, and scPDSI smoothed by 5-year Gauss filter for the territory of the Czech Republic in the period 1881–2006 are illustrated in Fig. 2. All three drought indices show a clear decreasing trend in the period studied, i.e., an increasing tendency to longer and more intensive dry episodes. Values of statistically significant decreasing trends reach −0.024/10 years for 12-month SPI, −0.048/10 years for the scZ-index and −0.192/10 years for scPDSI. Although several extremely dry and severely dry patterns emerged, the droughts in the mid-1930s, late 1940s–early 1950s, late 1980s–early 1990s and early 2000s were the best expressed. Turning to the scPDSI values, the episode in the early 1990s was the most severe. The drought from the late 1940s to the early 1950s is comparable with the previous episode only from the point of view of its duration. A prevailing trend towards more intensive and prolonged drought in Central Europe has been confirmed in a study by Trnka et al. (2008), based on data from selected stations. As the SPI allows tracking of drought tendencies driven only through precipitation changes we consider the scZ-index and scPDSI (that also take into account changes in the air temperature) as more suitable tools for evaluating long-term drought trends.

4.2 Cyclicity of droughts

Analysis of drought cyclicity in the Czech Republic based on scZ-index and scPDSI series was performed by the method of maximum entropy spectral analysis (MESA, see e.g., Olberg 1982; Olberg and Rákóczi 1984). ME-spectra for spring (MAM), summer (JJA), autumn (SON) and

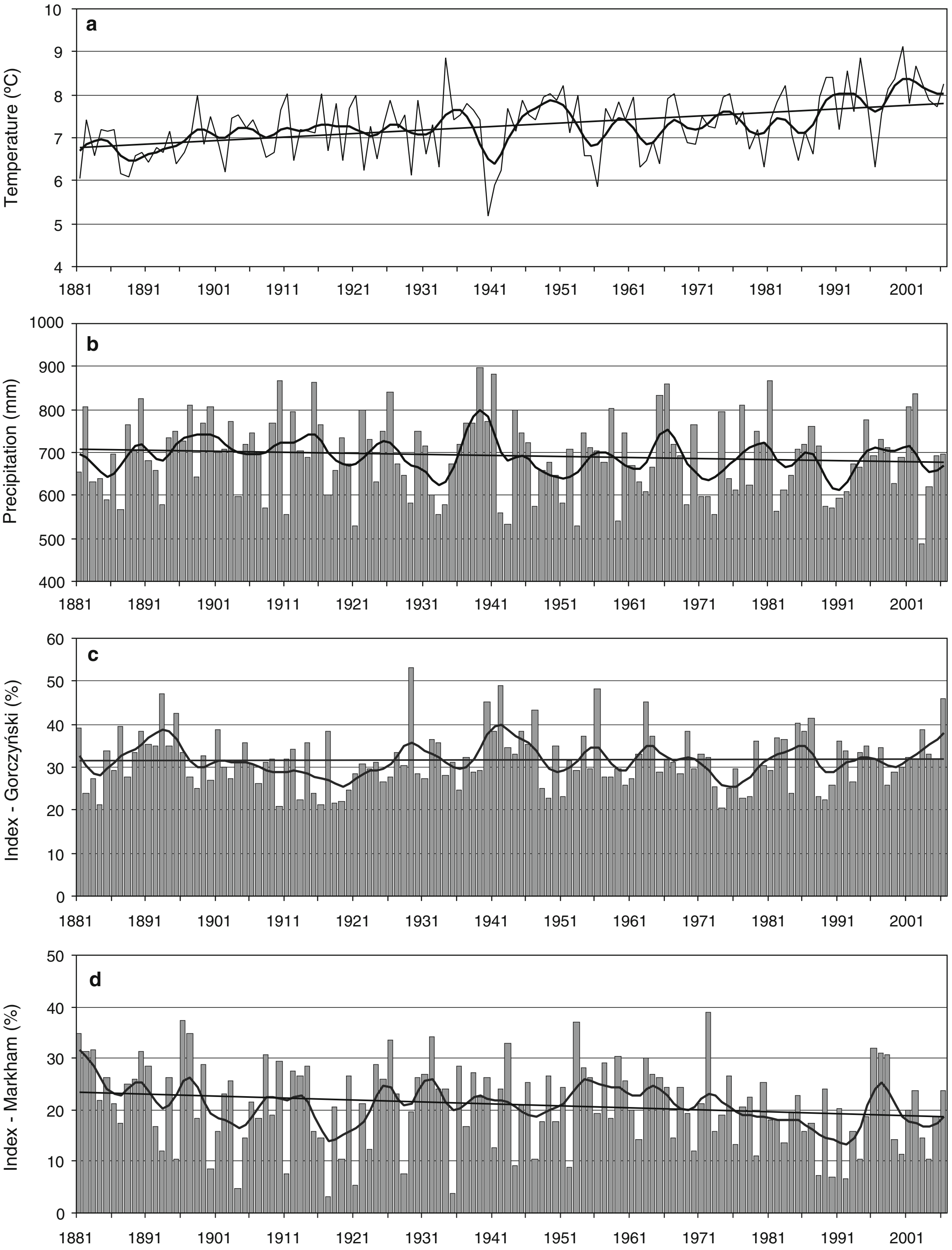

Fig. 1 Climate fluctuations in the Czech Republic in the period 1881–2006 (with linear trends and smoothed by Gauss filter over 10 years): **a** Annual air temperature (°C). **b** Annual precipitation totals (mm). **c** Index of temperature continentality after Gorczyński (%). **d** Index of precipitation seasonality after Markham (%)

vegetation period (April–September) are shown in Fig. 3. Although the spectral density of different cycles exceeded the 95% confidence level, they concentrate mainly at lengths of 3.4–3.5, 4.2–4.3, 5.0–5.1 and 15.4 years. A causal explanation of the cycles revealed is beyond the scope of this paper, although it may be noted that cycles longer than 10 years are usually associated with fluctuations in solar activity (see e.g., Benestad 2003) and shorter

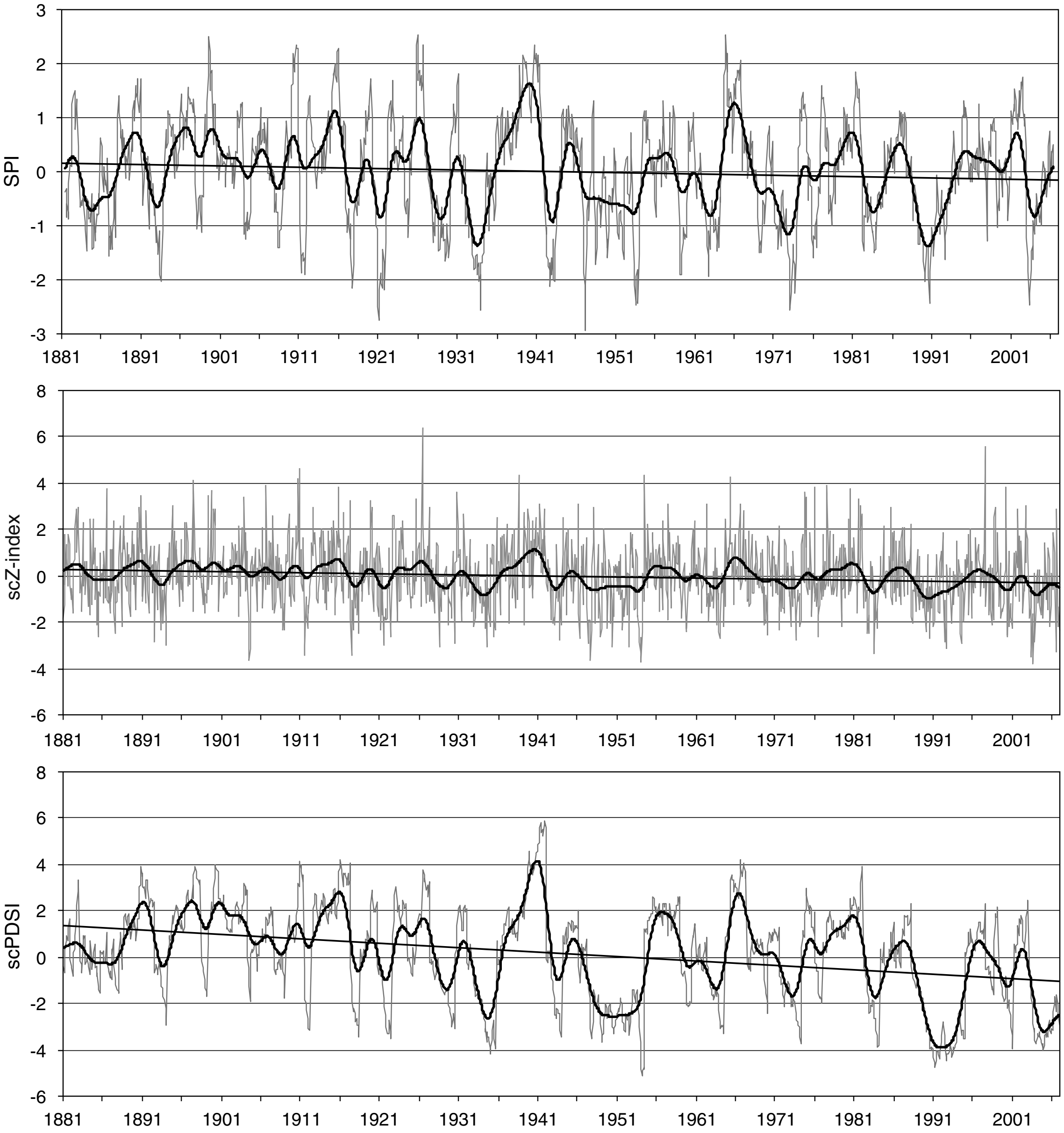

Fig. 2 Fluctuations in 12-month SPI, scZ-index, and scPDSI over the territory of the Czech Republic during the period 1881–2006, including corresponding linear trends and smoothing of the series by 5-year Gauss filter

cycles, in the range of 3–7 years, may follow from the internal variability of the atmosphere-ocean system reflected, for example, in the El Niño–Southern Oscillation (ENSO) phenomenon (for Central Europe, see e.g., Brázdil and Bíl 1998).

The method of dynamic MESA (Olberg 1982) may also be used for the study of the temporal stability of the cycles revealed. Figure 4 documents basic differences between the two drought indices used. Although some time intervals with significant short cycles (e.g., between 3 and 3.5 years) appear in the first and last thirds of the period studied for the scZ-index, longer cycles are typical of the scPDSI.

4.3 Synoptic climatology of droughts

The synoptic causes of droughts in the Czech Republic were studied with respect to severely dry and extremely dry months selected in the light of the scZ-index (Table 1). The first approach takes into consideration the frequency of occurrence of synoptic situations after the classification created by Brádka et al. (1961) and continuously extended by a team from the Czech Hydrometeorological Institute (Katalog 1967), but only for days after 1946. The basic idea was to classify synoptic processes according to the direction of airflow and the character of circulation

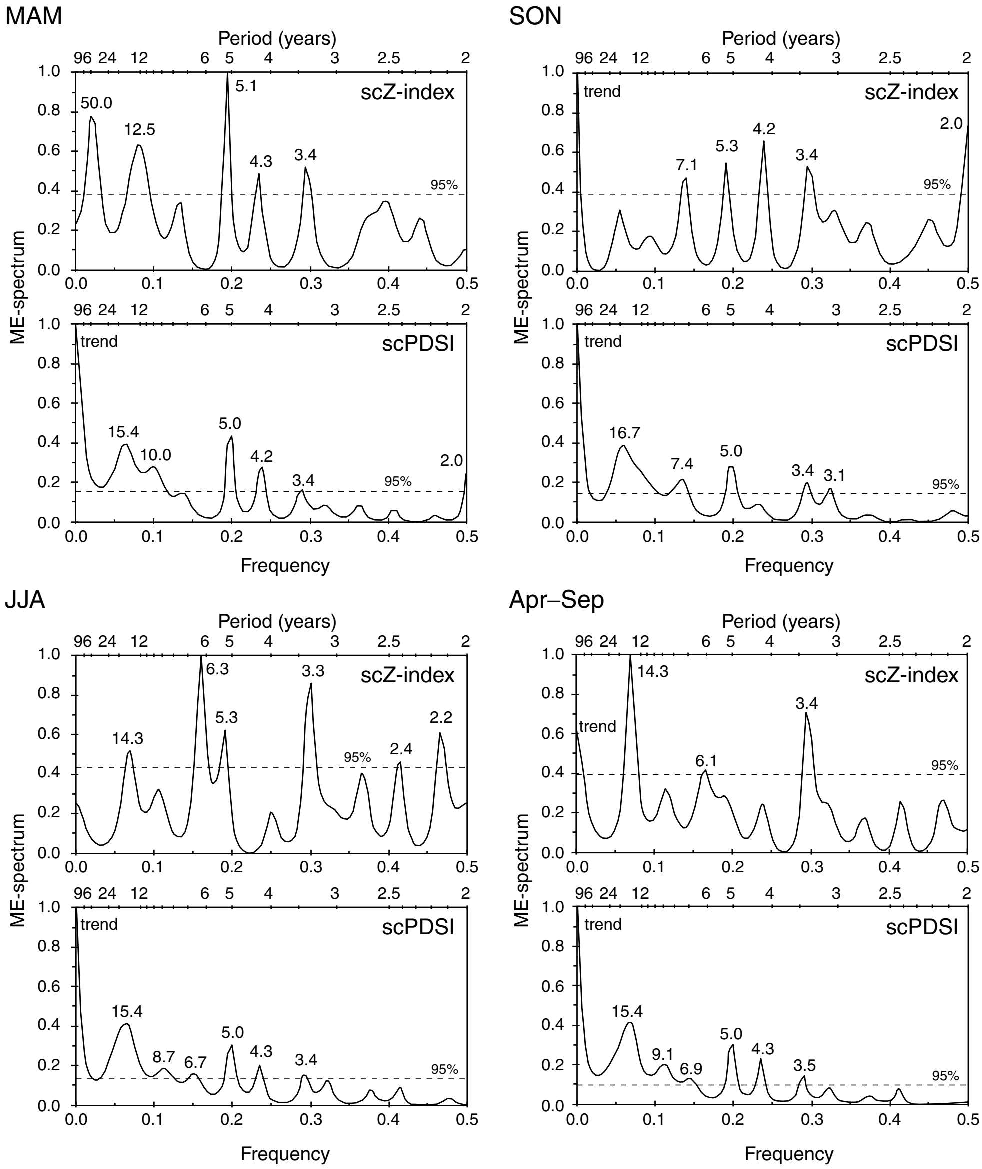

Fig. 3 Normalized ME-spectra of scZ-index and scPDSI (MAM, JJA, SON, April–September) for the Czech Republic in the period 1881–2006. The numbers express cycles (in years) which exceed the 95% confidence level. Peaks in ME-spectra for the frequency of 0.0 indicate the linear trend in series

(cyclonic or anticyclonic) during the natural synoptic period. Types of synoptic situations were derived from the basic features of pressure systems, the frontal zones, and frontal systems from the greater set of similar situations. The catalog lists 28 types of synoptic situation (for their list and schemes, see e.g., Brázdil et al. 2007b; Řezníčková et al. 2007). This classification was used rather than the better-known classification by Hess and Brezowsky developed for Germany (e.g., Hess and Brezowsky 1977; Gerstengarbe and Werner 1993) which is territorially shifted for the territory of the Czech Republic.

Differences between relative frequencies of situations occurring in selected extremely dry (severely dry) months and the reference period 1961–1990 (Fig. 5) show a generally expected decrease in frequencies of wetter cyclonic situations and an increase in drier anticyclonic ones. The most spectacular is expressed for negative departures in frequencies of situation Wc (western cyclonic – only winter half-year), A (anticyclone over Central Europe – only winter half-year) and B (trough over Central Europe) on the one hand and positive departures of the situation SEa (south-eastern anticyclonic), Ea (eastern anticyclonic), Sa (southern anticyclonic) and Wa (western anticyclonic) in the winter half-year on the other. These differences are higher for extremely dry months than for severely dry ones.

The second approach towards characterizing macro-scale circulation patterns during drought episodes is based on analysis of sea-level pressure (SLP) conditions using principal component analysis (PCA – see e.g., Barry and Carleton 2001). Mean monthly SLP fields provided by the Met. Office Hadley Centre (Allan and Ansell 2006) were used for the analysis. The spatial resolution of the HadSLP2 database is 5

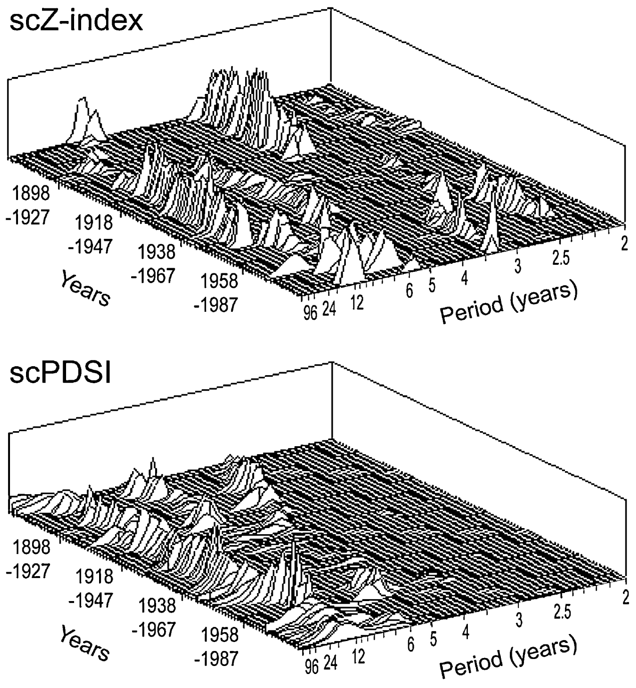

Fig. 4 Dynamic ME-spectra of scZ-index and scPDSI (April–September) for the Czech Republic in the period 1881–2006 (length of the basic period 30 years, step 1 year). Only the cycles exceeding the 95% confidence level are indicated

degrees of latitude-longitude and the data covers the period from 1850 to 2004. Using 250 grid-points extending from 70°W, 70°N to 50°E, 25°N, mean SLP fields for the reference period 1961–1990 were calculated (Figs. 6a, 7a). Further mean SLP fields for extremely and severely dry months were constructed. Circulation patterns typical of dry periods selected by means of scZ-index values were highlighted as departures from normal conditions (Figs. 6b, 7b). Because of significant differences between summer and winter circulation in the Atlantic-European area, drought patterns were studied separately for the winter half-year (October–March) and the summer half-year (April–September). Further, typical dry period circulation patterns were characterized by interpreted component scores, calculated through PCA.

In extremely dry months of the winter half-year (six cases), there is an important pressure increase in Eastern Europe, i.e., an intensification of the ridge of the Siberian High in Central Europe with a flow of dry continental air (Fig. 6). The Icelandic Low therefore deepens. The first principal component (PC) explains 92.4% of the total variance, i.e., the character of the SLP field is very uniform in all the months studied. This confirms the importance of the influence of high pressure in Central Europe associated with the ridge of the Siberian High.

In extremely dry months of the summer half-year (22 cases), absolute changes in the SLP field are not as strongly expressed as in the previous case. An increase in SLP for Western and Central Europe is reflected in a more pronounced Azores High and its ridge to Central Europe, also expressed by the first PC explaining 89.1% of the total variance (Fig. 7).

Severely dry months tend to reflect similar situations, although the first PC explains a smaller share of variance − 82.6% for the months of the winter half-year (36 cases) and 78.7% for months of the summer half-year (40 cases). However, in these cases, the share of other PCs is also very small. For example, the second PC explains only 6.6 and 6.1% of total variance, the third PC 3.6 and 5.7%, etc. As in extremely dry events, drought in the months of the winter half-year is associated with the ridge of the Siberian High (Fig. 8a) and in the summer half-year with the ridge of the Azores High (Fig. 8b).

5 Discussion and conclusions

The results of drought analysis in the territory of the Czech Republic during the period 1881–2006 show a clear tendency towards prolongation and greater severity of drought episodes. This is mainly due to the process of global warming (IPCC 2007), also reflected in an air temperature rise in the Czech Republic; changes in precipitation totals do not appear so crucial, although an insignificant decrease also appears here. The coherency of drought indices series with temperatures (Fig. 9) in the

Table 1 Category of droughts according to the Palmer scZ-index, drought severity index (scPDSI) and SPI

scZ-index	scPDSI	SPI	Drought category
≥3.50	≥4.00	≥2.00	Extremely wet
3.49 to 2.50	3.99 to 3.00	1.99 to 1.50	Severely wet
2.49 to 1.00	2.99 to 2.00	1.49 to 1.00	Wet
0.99 to −1.24	1.99 to −1.99	0.99 to −0.99	Normal
−1.25 to −1.99	−2.00 to −2.99	−1.00 to −1.49	Dry
−2.00 to −2.74	−3.00 to −3.99	−1.50 to −1.99	Severely dry
≤−2.75	≤−4.00	≤−2.00	Extremely dry

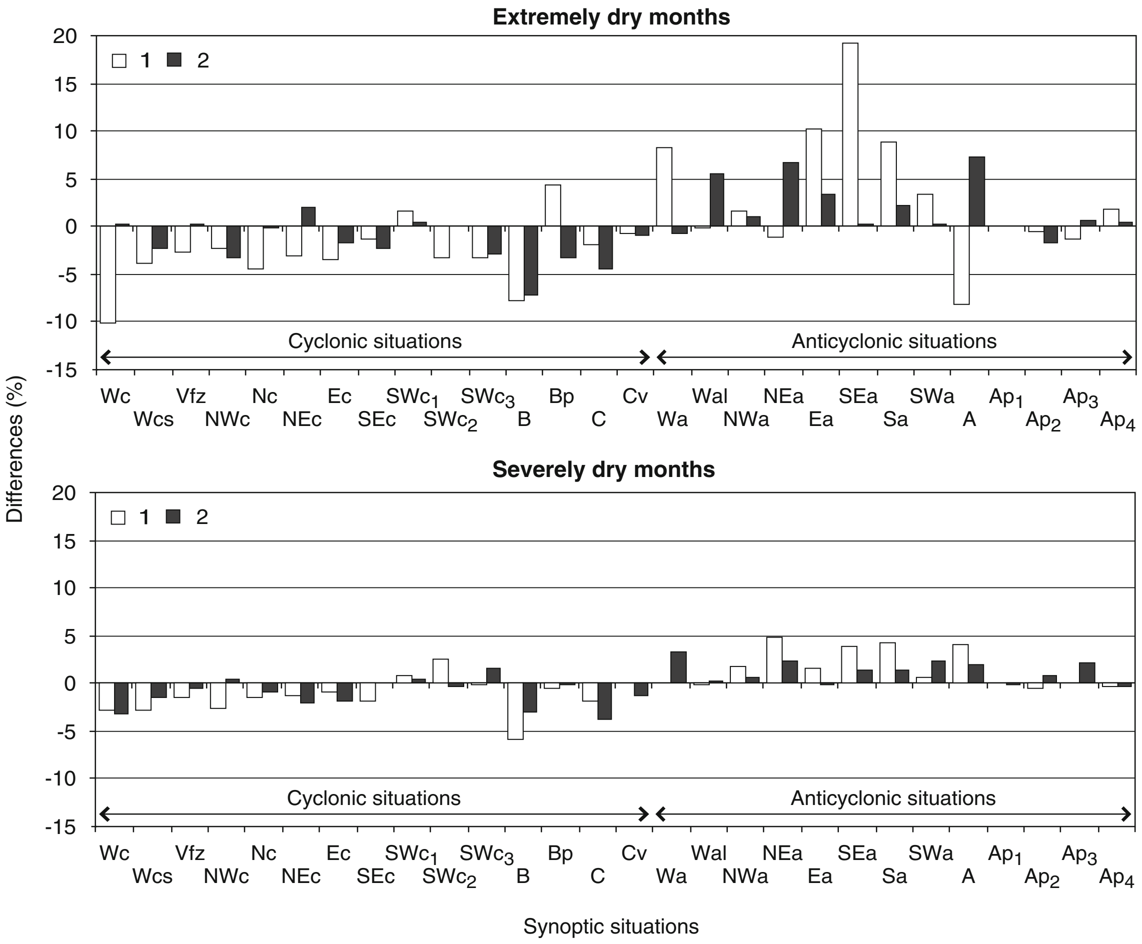

Fig. 5 Differences in relative frequencies (%) of the occurrence of synoptic situations (Katalog 1967) in extremely dry and severely dry months (see Table 1 for definition) selected in the Czech Republic according to scZ-index (1946–2006) with respect to normal patterns (1961–1990): *1* Winter half year (October–March), *2* Summer half-year (April–September)

vegetation period (April–September) exceeds 95 and 99% confidence levels only for some cycles (trend, 12.5, 3.3, and 3.1, 2.6, and 2.5 years), while coherency coefficients with precipitation totals exceed both confidence levels for all cycles in the case of scZ-index and for cycles longer than 5 years for scPDSI (for calculation of coherency coefficients see Schönwiese 1985).

The increasing air temperature leads to higher potential evapotranspiration estimates in the water-balance model of both scZ-index and scPDSI, which in combination with an evident (although not significant) decrease of precipitation leads to a higher probability of soil moisture deficit. This is the primary cause of the high coherency between the statistically significant trend for air temperature and trends in both drought indices. The results for shorter cycles, however, indicate that precipitation is the principal meteorological element driving soil moisture dynamics in Central Europe. This is in line with the commonly held view that precipitation deficit is the primary cause of individual drought episodes in the region, with the temperature seen as a moderating or intensifying factor.

The frequency of anticyclonic situations, together with the temperature and precipitation patterns of the two most important drought episodes in the Czech Republic selected according to scPDSI (April 1947–June 1954 and April 1988–December 1994) were studied with respect to the reference period 1961–1990 (Fig. 10). The first drought episode shows a clear prevalence of above-normal anticyclonic situations in many months, more very dry months (18 months with precipitation totals lower than 50% of the corresponding mean) and relatively smaller positive temperature anomalies (but in 2 months higher than 4.0°C). During this period, short sequences of wet months also appeared, mainly from November 1947 to February 1948 and from September to November 1952, but their occurrence in the months of the winter half-year did not significantly affect the dryness of the whole episode, largely due to comparatively lower precipitation totals

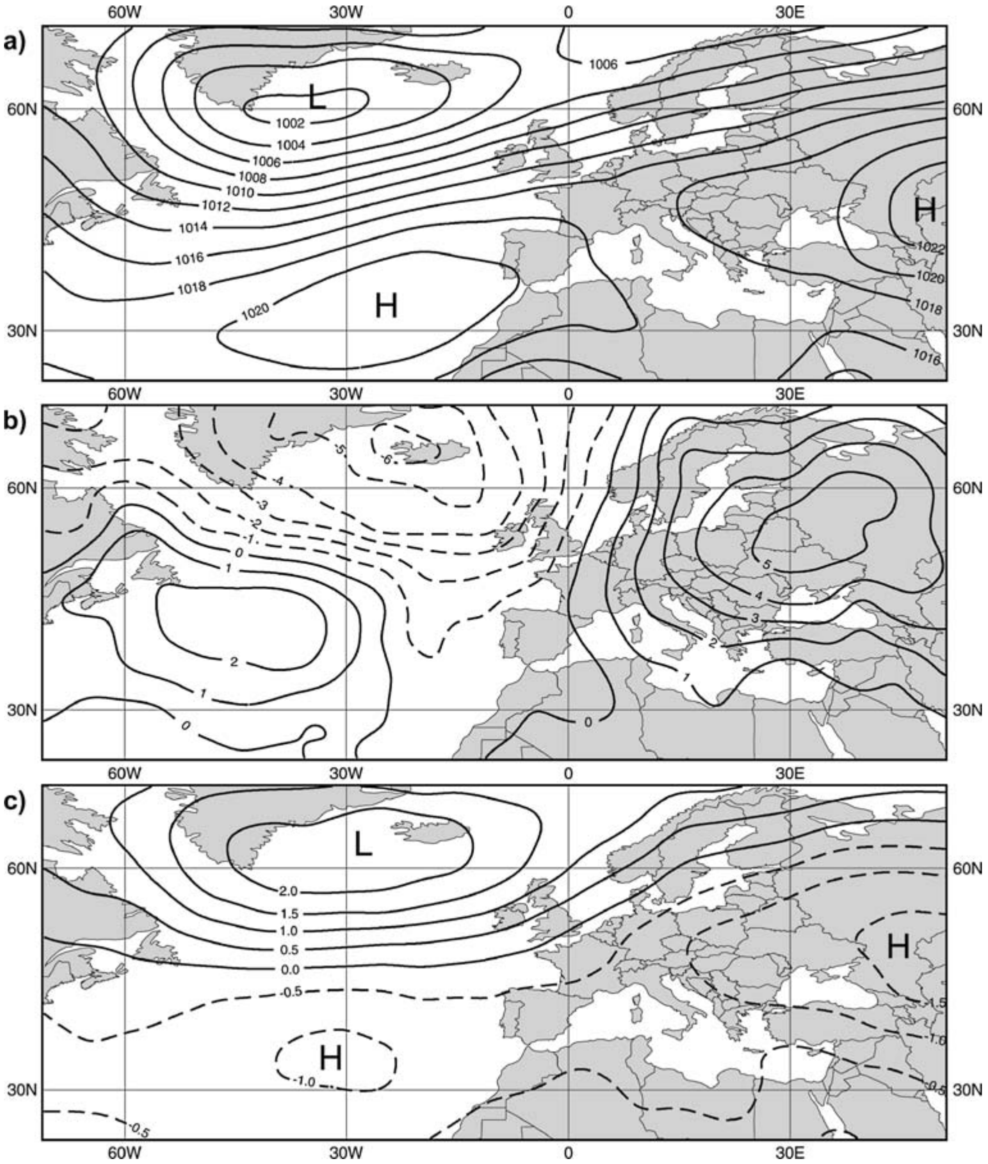

Fig. 6 Winter half-year: **a** Mean SLP in the Atlantic-European area in the reference period 1961–1990. **b** Deviations (hPa) of composite mean SLP of extremely dry months (see Table 1 for definition) from mean SLP in the reference period 1961–1990. **c** Interpreted component scores of the first PC for SLP in extremely dry months; *H* High, *L* Low

during the winter half-year. In the second drought episode, in the late 1980s–early 1990s, the frequency of anticyclonic situations was close to normal, which is surprising given the duration and intensity of drought during this period. The dryness of this episode was related to the frequent occurrence of dry months (wet months with totals ≥150% of the corresponding mean appeared almost exclusively during winter half-year) and higher temperatures, often with departures of more than 2.0°C.

The existence of drying trends in the Czech Republic corroborates the findings of Szinell et al. (1998), who reported regionally specific, but nevertheless significant, trends in scPDSI values towards a drier climate at 15 stations in Hungary, and of Horváth (2002), who reported similar results for the River Tisza catchment. Dai et al. (1998) noted that the area under the influence of drought increased in Europe between 1960 and 1995; however, this rise was found to be of the same magnitude that Europe had already experienced in the early 1920s and late 1940s. In subsequent work applying the scPDSI to the 1870–2002 time series, Dai et al. (2004) described a notable drying trend throughout Central Europe (including the Czech Republic), beginning at the start of the 20th century, which was linked to increasing temperatures within the same time frame. Similarly, van der Schrier et al. (2006) noted quite strong drying trends in Central Europe based on scPDSI for the summer months (between 1950 and 2002) in the area located east of 15°E. On the other hand, studies by Frich et al. (2002), Moberg and Jones (2005) and Schmidli and Frei (2005) did not indicate significant drying trends in this region. This is understandable, since in these studies the degree of dryness was evaluated in terms of consecutive

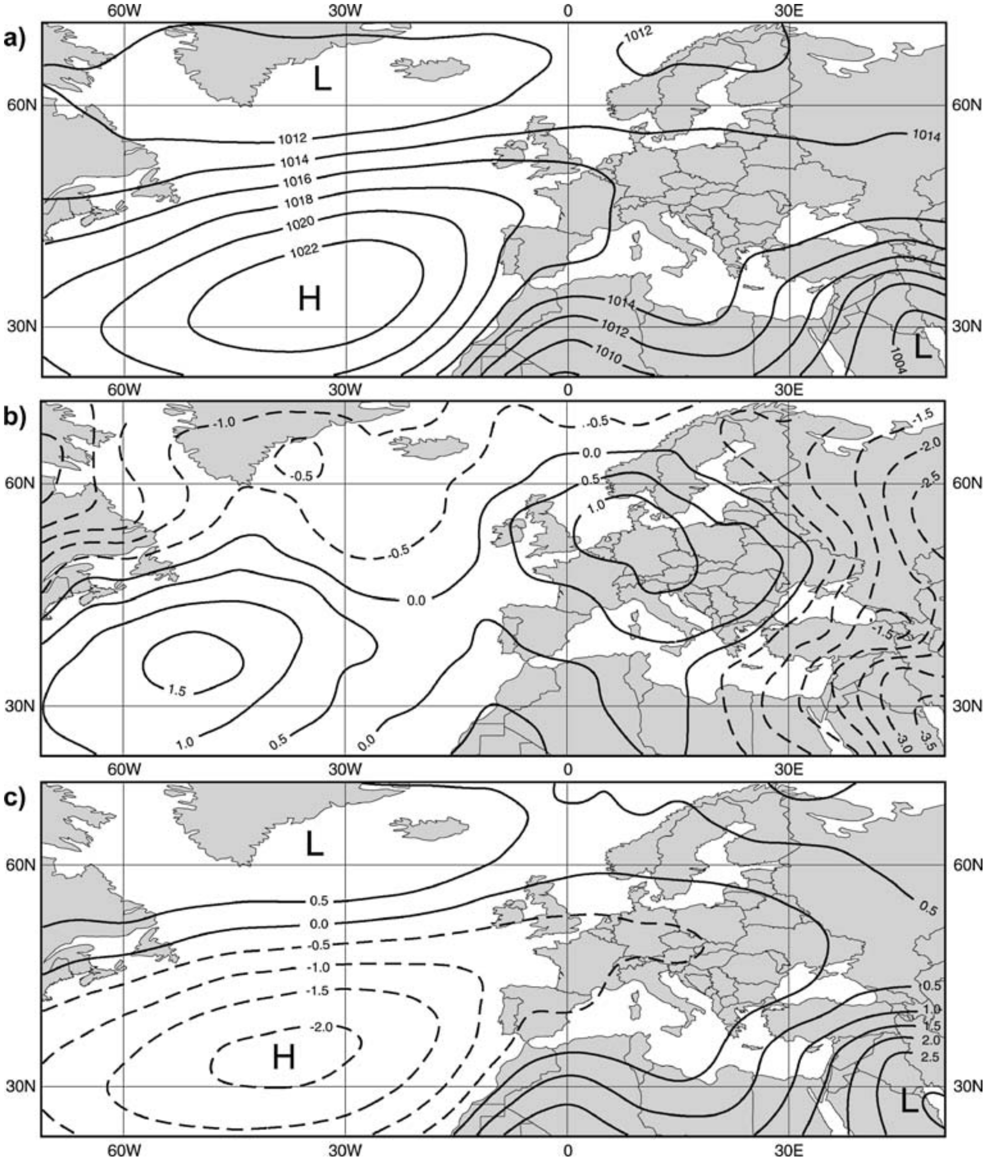

Fig. 7 Summer half-year: **a** Mean SLP in the Atlantic-European area in the reference period 1961–1990. **b** Deviations (hPa) of composite mean SLP of extremely dry months (see Table 1 for definition) from mean SLP in the reference period 1961–1990. **c** Interpreted component scores of the first PC for SLP in extremely dry months; *H* High, *L* Low

days without precipitation rather than in terms of soil moisture anomaly. Using the number of dry days takes only one component of landscape water balance (frequency of rainfall) into account but completely omits changes on the demand side, as well as changes in precipitation totals. Most of the studies based on observed data in the Central European region show a statistically significant increase in temperatures during the 20th century, while a tendency towards higher precipitation was found only during the winter. The changes that occurred in the precipitation parameters evaluated during the summer half-year were mainly insignificant (Frich et al. 2002; Moberg and Jones 2005; Schmidli and Frei 2005; Hundecha and Bárdossy 2005; Chládová et al. 2007). In addition, analysis of the annual cycle of trends of selected climatic elements in the Czech Republic shows a rather pronounced tendency towards higher temperatures and lower precipitation during most of the April–June period (Moliba et al. 2006). According to the projections of global circulation models for the Czech Republic (e.g., Dubrovský et al. 2005), an increase in potential evapotranspiration (driven by the temperature increase) will not be met by an adequate increase in precipitation, which will inevitably lead to a higher frequency of droughts, as the studies of Dubrovský et al. (2007a, b) have indicated.

As has been shown in various papers (e.g., Quiring and Papakryiakou 2003; Scian 2004; Trnka et al. 2007b), the impacts of meteorological drought are very important to agriculture in much of temperate zone, including Central Europe. Agriculture in this region is most vulnerable to prolonged droughts during early spring, since it reduces survival and stand density leading, in some cases, to

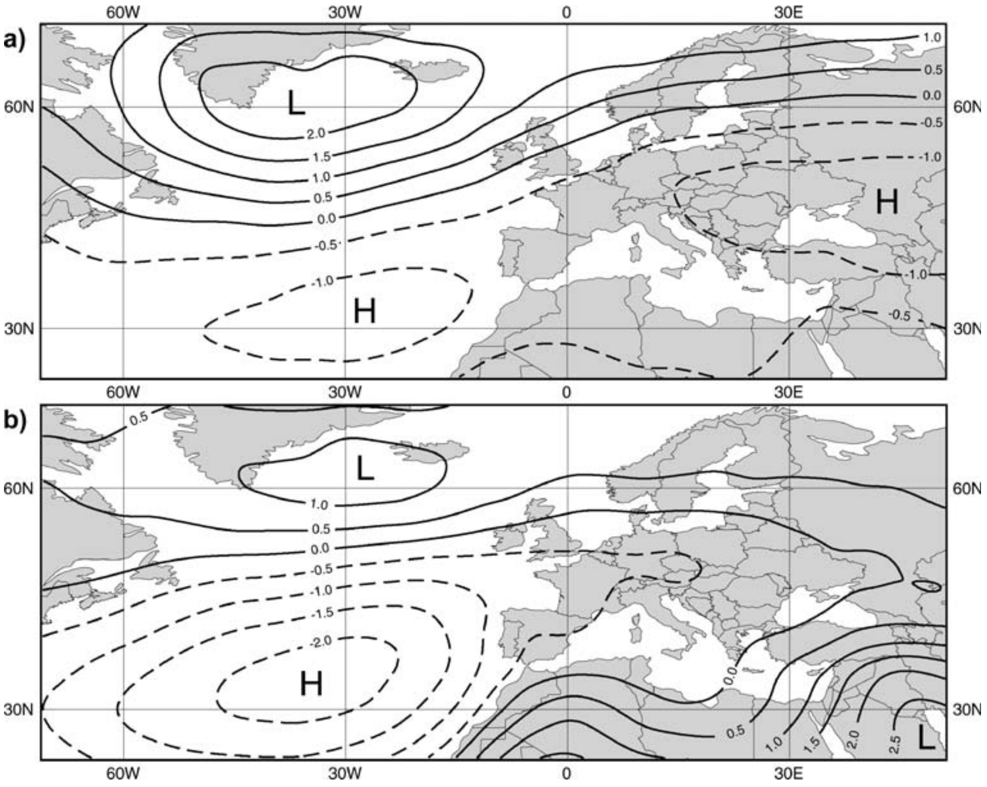

Fig. 8 Interpreted component scores of the first PC for SLP in the Atlantic-European area in severely dry months (see Table 1 for definition) of the winter half-year (**a**) and the summer half-year (**b**): *H* High, *L* Low

complete crop failure (as was the case in the droughts of 1947 and 2000). Drought during anthesis and/or grain filling periods adversely affects grain numbers and mass. This occurred in some regions in 1947, when the combination of a long winter, which led to late sowing, and severe drought, peaking in May and then September, were the main causes of poor emergence of spring crops and of slow growth with unsatisfactory tillering. The drought impacts were most severe in the south-east of the Czech Republic and on sandy soils; they resulted in a reduction of up to 70% in regional yields of cereals (especially winter wheat) and forage crops (Minář 1947).

The drought of 2000 lasted from April to June in the Czech Republic and was the primary reason for a poor spring crop, particularly in southern Czech Republic (similar to 1947), where the losses compensated to farmers

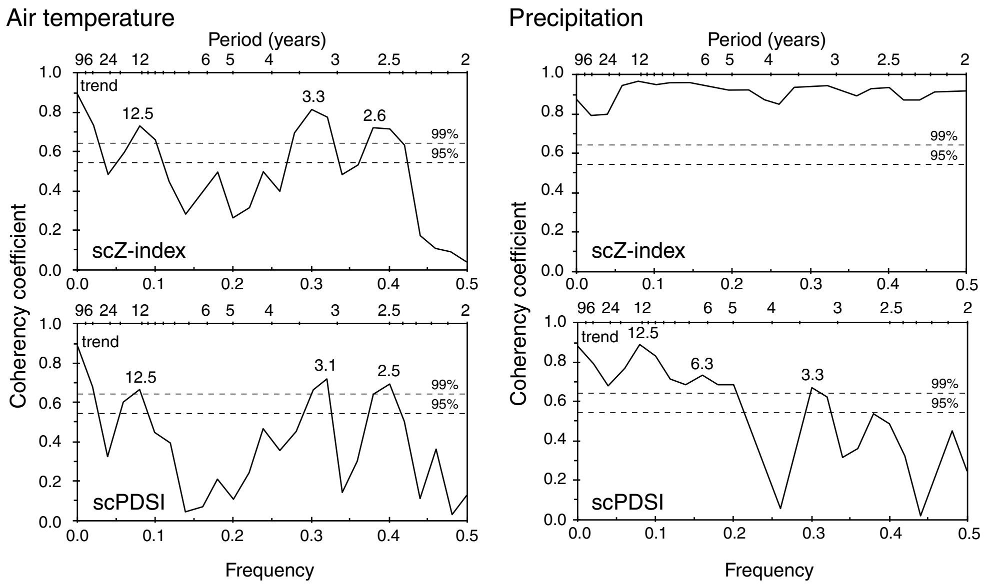

Fig. 9 Coherency coefficients of scZ-index and scPDSI series with air temperature and precipitation series of the Czech Republic in the vegetation period (April–September) 1881–2006. The numbers indicate cycles (in years) for which the coherency coefficients exceed the 95% and 99% confidence levels

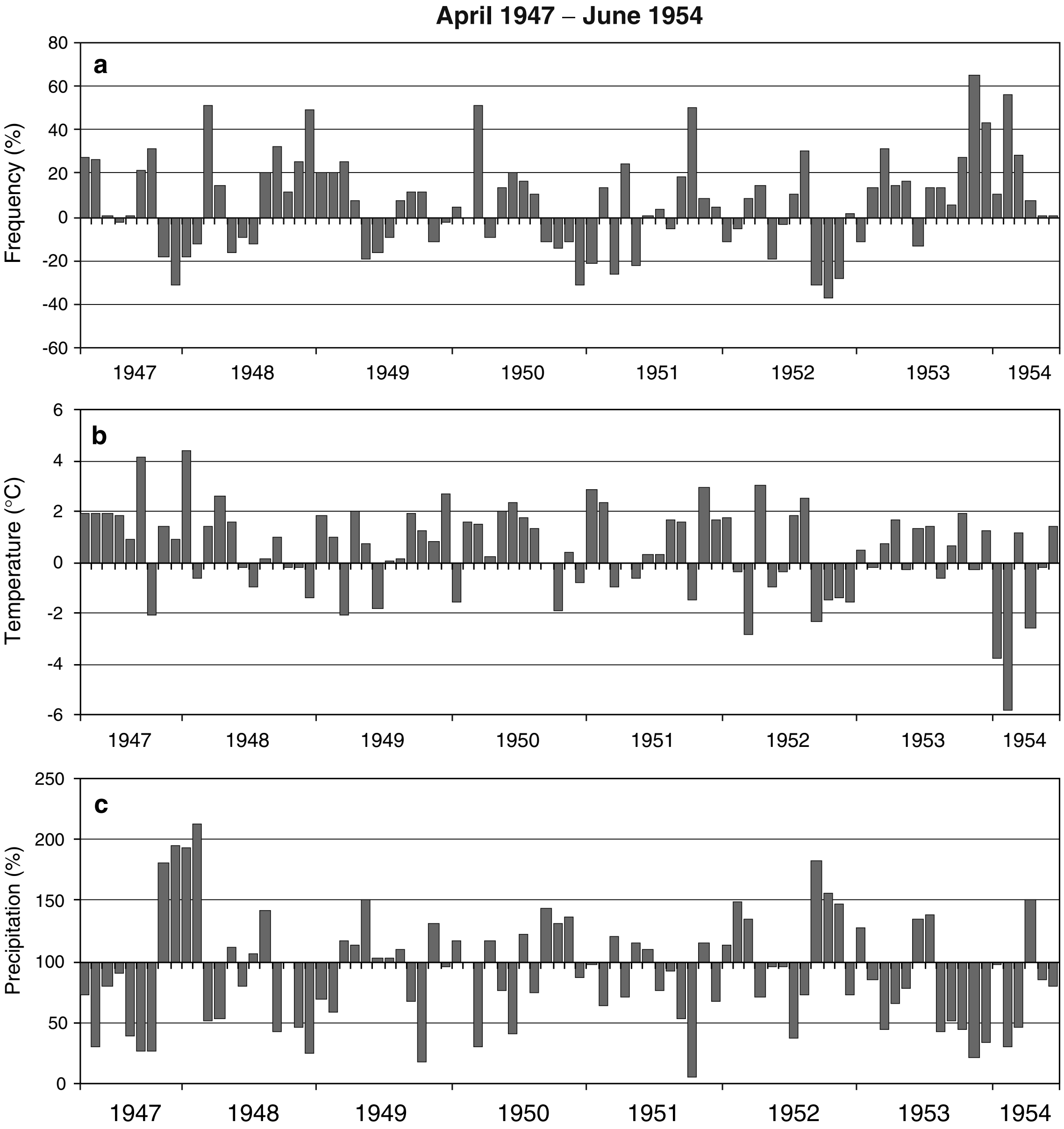

Fig. 10 Characteristics of two main drought episodes in the Czech Republic, selected according to scPDSI: **a**, **d** Departures in relative frequencies of anticyclonic situations (%). **b**, **e** Monthly temperature anomalies (°C). **c**, **f** Monthly precipitation anomalies (%). Reference period 1961–1990

from the state budget were as high as around 5 billion Czech crowns (approximately 185 million Euros). Figure 11a shows the effect of the intense drought on spring barley yields in 2000. The mean value of the relative Z-index (e.g., Dubrovský et al. 2007b; Trnka et al. 2007b) was calculated for arable land in 62 districts of the Czech Republic over the period 1961–2000 using a database of 233 meteorological stations (Tolasz et al. 2007). The districts with the highest drought intensity between April and June also show the highest negative deviations from the long-term yield mean. The intensity of drought during April–June may explain 64.8% of the variability in spring barley yields at district level. On the other hand, the drought of 2000 had much lighter impacts on winter wheat production (Fig. 11b). A far better developed root system and earlier onset of growth in the spring led to the reduction of wheat yields being less severe and widespread than that of spring barley. The drought intensity between April and June can explain only 25.2% of the variability in winter wheat yields between individual districts.

The effect of drought on agricultural production may also be observed on the national level, despite differences between the individual regions. For example, areas located at higher elevations with higher precipitation totals tend to be less

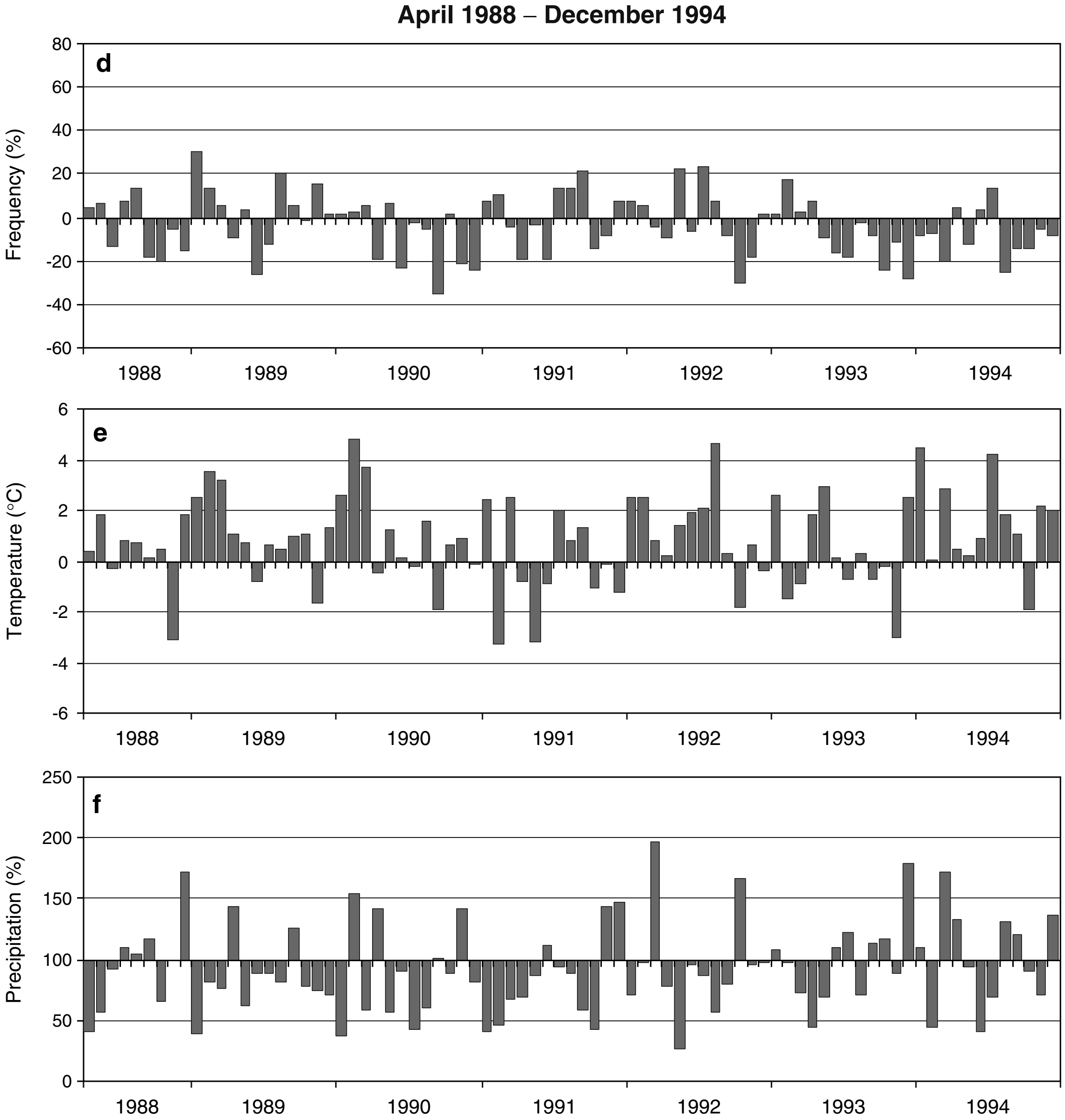

Fig. 10 (continued)

vulnerable to drought. There is an obvious tendency to below-average yields at Czech Republic level in almost all dry years (Fig. 12). This holds true not only for annual crops (both spring and winter) but also for perennials (grasslands used for hay production). The results presented in Fig. 12a match the findings of Arora et al. (1987), Petr (1987), Quiring and Papakryiakou (2003) and Zimolka (2006), who determined that spring cereal yield is sensitive to moisture stress during emergence, shooting, heading and early soft dough stages, developments that usually take place in the April–June period. Similar but less pronounced relationships were found between drought severity during October (wheat emergence) and April–June (shooting, heading and early soft dough) in the case of winter wheat (Fig. 12b). On the other hand, the seasonal water balance (April–July) can explain between 40 and 42% of variability in the national mean yields of forage crops on arable land and hay from meadows (Fig. 12c–d). Relationships between drought indices for the growing season and yields of all four crops are well represented by a second-order polynomial. This closely approximates the nature of the crop-yield water relationship (Ash et al. 1992) as crop yields may be inhibited not only through water stress but also by low global radiation, below-normal temperatures, root anoxia, and higher infestation pressure of fungal diseases, all factors that tend to be associated with unusually wet seasons. Further tests showed no improvement in model

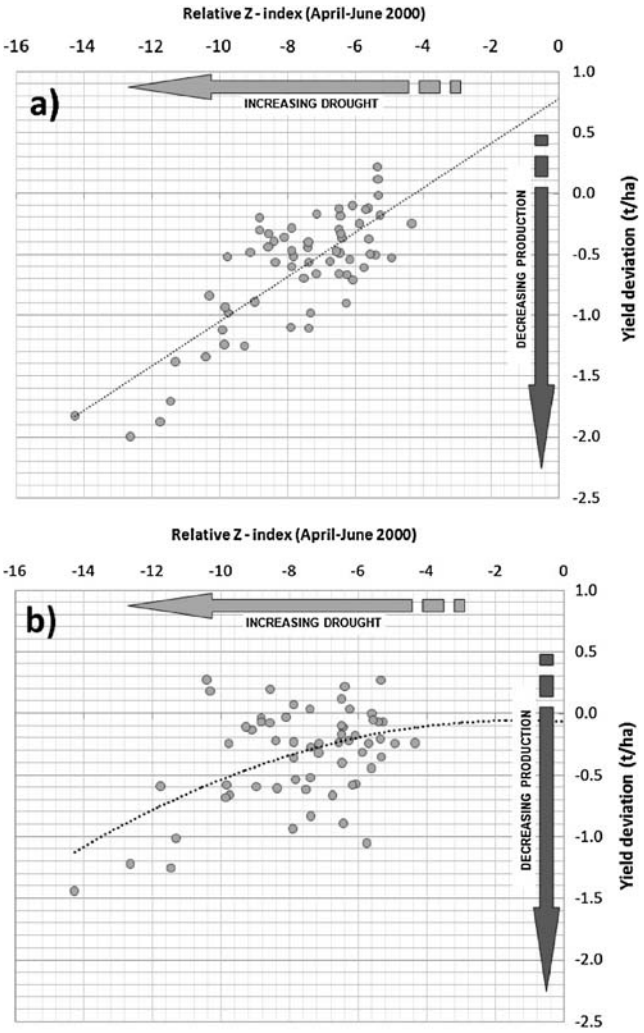

Fig. 11 Relationships between relative Z-index (Dubrovský et al. 2007b; see Section 2 for explanation) and yield deviation from long-term means (1961–2000) at 62 (spring barley) and 65 (winter wheat) districts of the Czech Republic during the drought year 2000 for spring barley (**a**) and winter wheat (**b**). The dotted line indicates the slope of regression function. In both cases, the yield departures are significantly correlated with the regional drought intensity, with a Pearson correlation coefficient of 0.79 and 0.47, respectively (significance level α=0.01). N.B: Of a total of 77 Czech Republic districts 15 (12) were excluded completely as yield data were available either for only a small portion of the evaluated period or over an insignificant acreage

results when higher-order polynomials were used, which is in accord with the findings of Yamoah et al. (2000) and Quiring and Papakryiakou (2003). The highest influence of drought on Czech national crop yields may be found in the years 1922, 1934, 1947, 1976, 1988, 1992, 1993, 2000, and 2003. The extraordinarily hot and dry summer of 2003 (for the Czech Republic see Pavlík et al. 2003) had not only agricultural consequences; between 22,000 and 35,000 heat-related deaths were recorded across Europe (e.g., Schär and Jendritzky 2004; Schönwiese et al. 2004; Trigo et al. 2005; Fischer et al. 2007). The 2 years with the wettest vegetation season (1926 and 1965) in the Czech Republic were associated with significant yield decreases for cereals and yield stagnation for forage crops and hay production.

Forestry is another sector vulnerable to droughts in the Czech Republic. For example, forest damage attributable to drought and air pollution grew from 1.8% in the period 1901–1950 to 18.1% in the next 30 years (Forst et al. 1985). Salvage felling of timber arising out of droughts reached 7.2% during the 1963–1999 period. The impacts of the early-1990s droughts can be particularly well documented. Corresponding damage from 1992–1994 was reflected, with a 1-year delay, in high values of salvage felling arising out of drought (Fig. 13). In 2001–2005, the percentage share of drought damage in the whole volume of salvage felling in the Czech Republic achieved ca. 11%, but in some years (e.g., 2004, 2005) it was as high as 20% (Brázdil et al. 2007b).

Observed drying trends in Central Europe are confirmed by model projections. For example, Pal et al. (2004) basing their work on regional climate model projections, identified Central Europe as being among the areas particularly vulnerable to an increase in summer droughts (and also floods), following the observed drying trend in Western/Central Europe over the past 25 years. According to the products of GCM HadCM3 for the SRES scenario A2 (see Houghton et al. 2001), a rise in mean temperature by 2–4°C in 2060–2099 may be anticipated in the Central European region, accompanied by only a small change in annual precipitation totals (Dubrovský et al. 2005). Annual variation of precipitation should also change, with a conspicuous increase in winter (by as much as 25%) and a reduction in summer. This could result in the desertification of the climate of Central Europe with inevitable consequences for the Czech Republic, where precipitation is the main source of water. One consequence may well be a multiple increase in the probability of occurrence of intense drought episodes (including the devastating) and also consequent changes in the water economy of the landscape, as has been documented by Dubrovský et al. (2007a, b).

Most of the scenarios employed for climatic change indicate a pronounced increase in territory endangered by drought, affecting the most productive agricultural regions. Such a development would mostly affect southern Moravia, the driest south-eastern part of the Czech Republic. In terms of forest economy, this represents a considerable risk of forest fires in combination with higher summer temperatures, reduction of reserves of soil water and a deficit in precipitation. Original and partly changed ecosystems, or the remnants thereof, will also be endangered because conspicuous aridation will considerably change the conditions for many stands. This is one example of the crucial importance of studies devoted to drought, developing a better scientific understanding of events and preventive mitigation of the anticipated impacts of the climate of the future.

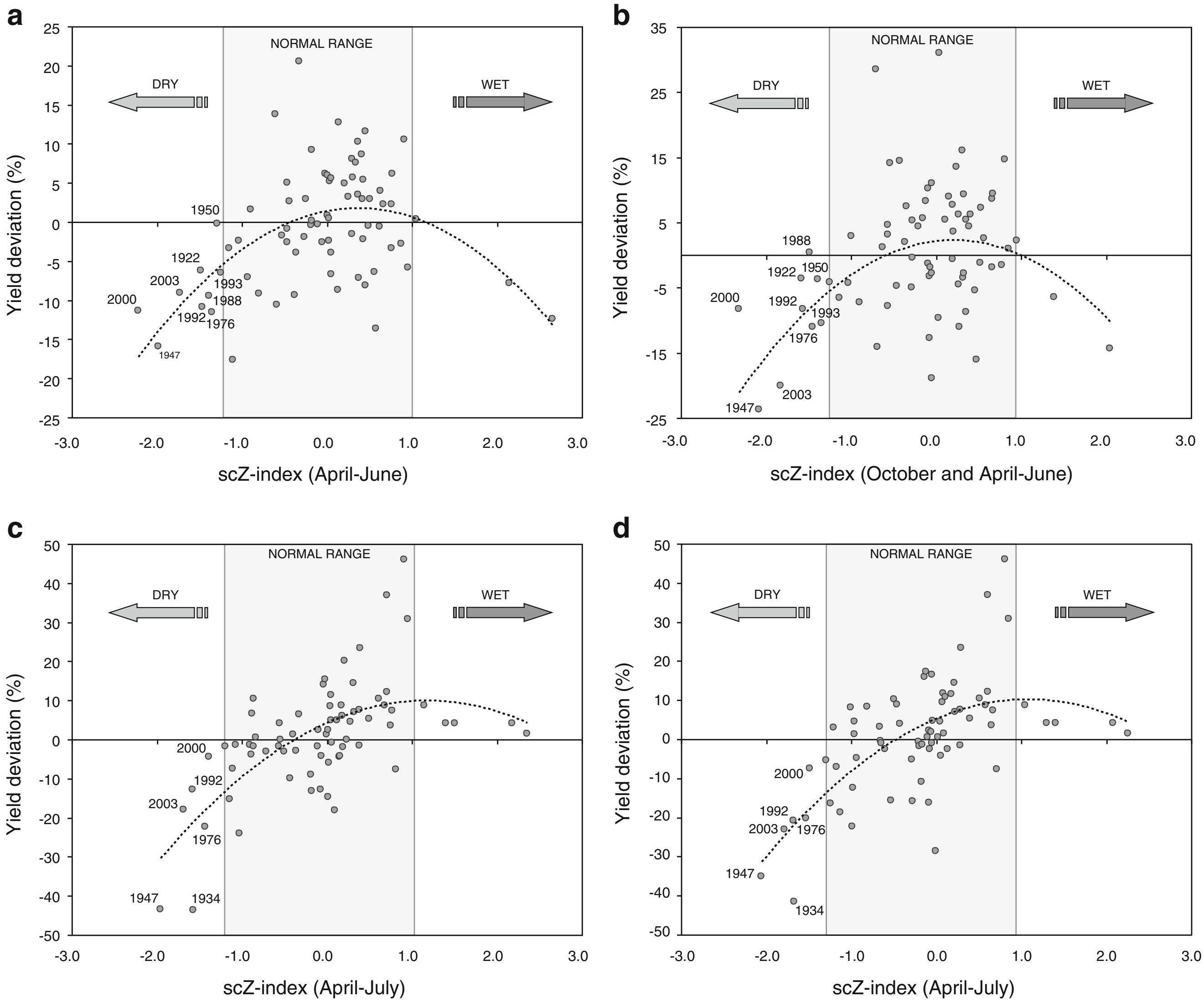

Fig. 12 Relationships between scZ-index and yield deviations from a 5-year running average of selected crops of **a** spring barley, **b** winter wheat, **c** forage crops on arable land and **d** hay from meadows in different months for the Czech Republic in the period 1918–2006 (with the exception of 1939–1944). In all cases, the yield departures are significantly correlated with drought intensity, with a Pearson correlation coefficient of **a** 0.55; **b** 0.43; **c** 0.63 and **d** 0.65 respectively (significance level α=0.01). The dotted line indicates the course of a second-order polynomial function

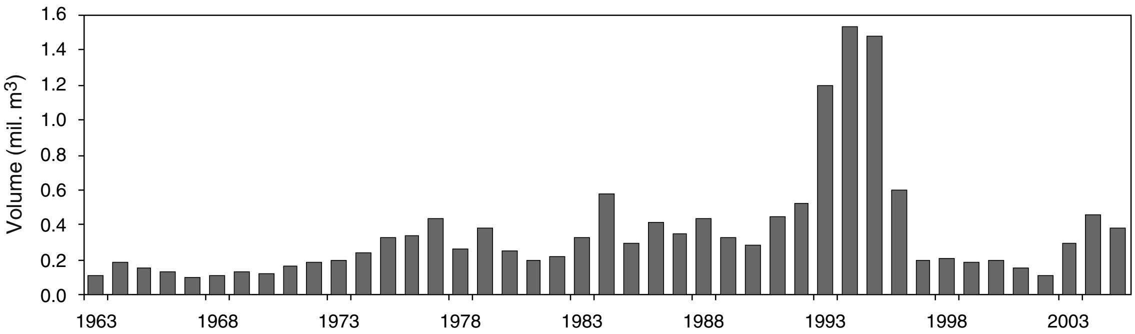

Fig. 13 Volume of salvage felling (million m^3) due to drought in the Czech Republic during the period 1963–2005 (source: Research Institute of Forestry Economy and Gamekeeping, Jíloviště-Strnady; data after 1990 cover approximately three-quarters of the forest area in the Czech Republic) (Brázdil et al. 2007b)

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