Drought trends over part of Central Europe between 1961 and 2014

Miroslav Trnka[1,2,*], **Jan Balek**[1,2], **Petr Štěpánek**[1,3], **Pavel Zahradníček**[1,3], **Martin Možný**[2,4], **Josef Eitzinger**[5], **Zdeněk Žalud**[1,2], **Herbert Formayer**[5], **Maroš Turňa**[6], **Pavol Nejedlík**[7], **Daniela Semerádová**[1], **Petr Hlavinka**[1,2], **Rudolf Brázdil**[1,8]

[1]Global Change Research Institute, Czech Academy of Sciences, Bělidla 986/4a, 603 00 Brno, Czech Republic
[2]Department of Agrosystems and Bioclimatology, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic
[3]Czech Hydrometeorological Institute, Brno Regional Office, Kroftova 2578/43, 616 67 Brno, Czech Republic
[4]Czech Hydrometeorological Institute, Doksany Observatory, Doksany 105, 411 85 Doksany, Czech Republic
[5]University of Natural Resources and Life Sciences, Institute of Meteorology, Peter-Jordan Strasse 82, 1190 Vienna, Austria
[6]Slovak Hydrometeorological Institute, Jeséniova 17, 833 15 Bratislava, Slovakia
[7]Earth Science Institute, Slovak Academy of Science, Dúbravská cesta 9, 845 28 Bratislava, Slovakia
[8]Institute of Geography, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic

ABSTRACT: An increase in drought frequency, duration and severity is expected for the Central European region as a direct consequence of climate change. This will have profound effects on a number of key sectors (e.g. agriculture, forestry, energy production and tourism) and also affect water resources, biodiversity and the landscape as a whole. However, global circulation models significantly differ in their projections for Central Europe with respect to the magnitude and timing of these changes. Therefore, analysis of changes in drought characteristics during the last 54 yr in relation to prevailing climate trends might significantly enhance our understanding of present and future drought risks. This study is based on a set of drought indices, including the Standardized Precipitation Index (SPI), the Palmer Drought Severity Index (PDSI), the Palmer Z-index (Z-index) and the Standardized Precipitation–Evapotranspiration Index (SPEI), in their most advanced formulations. The time series of the drought indices were calculated for 411 climatological stations across Austria (excluding the Alps), the Czech Republic and Slovakia. Up to 45% of the evaluated stations (depending on the index) became significantly drier during the 1961–2014 period except for areas in the west and north of the studied region. In addition to identifying the regions with the most pronounced drying trends, a drying trend consistency across the station network of 3 independent national weather services was shown. The main driver behind this development was an increase in the evaporative demand of the atmosphere, driven by higher temperatures and global radiation with limited changes in precipitation totals. The observed drying trends were most pronounced during the April–September period and in lower elevations. Conversely, the majority of stations above 1000 m exhibited a significant wetting trend for both the summer and winter (October–March) half-years.

KEY WORDS: SPI · PDSI · SPEI · Z-index · ICDI · Drought climatology · Climate trends

1. INTRODUCTION

Drought is referred to as the most complex and least understood of all natural hazards, affecting more people than any other extreme event (Wilhite 2000). Any realistic definition of drought must be region- and application-specific. Four interrelated categories of drought are usually distinguished based on the time scale and impact: meteorological, agricultural, hydrological and socioeconomic (Heim 2002). Agricultural drought impacts are mostly associated with timescales from weeks to 6–9 mo, while

*Corresponding author: mirek_trnka@yahoo.com

hydrological and socioeconomic impacts usually become apparent following longer time lags. The individual drought categories and their timescales obviously overlap. The occurrence of meteorological drought, however, precedes the onset of specific impacts and thus it is extremely important to understand the regional characteristics of meteorological drought before studying its specific impacts. For this purpose, different drought indices are frequently used to examine meteorological drought, because they are convenient and relatively simple to calculate (Wardlow et al. 2012).

The importance of systematic research on drought climatology has been recognized across the world (Wilhite 2005) and particularly in countries/regions where water supply depends on seasonal precipitation patterns or snow accumulation as the main water source (e.g. the Colorado River basin; Christensen et al. 2004). Incorrectly estimating drought risk or omitting drought-related issues in the process of strategic planning can have serious consequences, not only for the stability of remaining natural ecosystems but also for the economy and society as a whole. A prolonged dry spell may not only inflict severe economic losses, but it can potentially paralyze agricultural production over several seasons and restrain other segments of the economy as well (White et al. 2003, Horridge et al. 2005). Global (Dai 2013) as well as regional studies (Calanca 2007, Trnka et al. 2013, Hänsel et al. 2014) indicate that increased drought probability is to be expected during the 21st century as a direct impact of ongoing climate change.

The high vulnerability and devastating effects of droughts that are commonly associated with specific climatic regions (e.g. African Sahel or recently Australia) are rarely experienced in Central Europe. This region is instead faced with so-called 'green droughts', i.e. droughts associated with relatively ample annual precipitation totals (compared to arid regions) but reduced agricultural productivity due to poorly timed rains. However, even here, drought episodes have played an important role since the early Neolithic Age, when relatively short drought periods significantly influenced the location of early settlements (Kalis et al. 2003). The dendroclimatic data and documentary sources indicate several cases of droughts with intensity not recorded during the instrumental period (Büntgen et al. 2011a, Brázdil et al. 2013, Cook et al. 2015, Dobrovolný et al. 2015). However, even the relatively short instrumental records provide a clear indication of the occurrence of persistent drought periods (e.g. van der Schrier et al. 2006) in this region. The most severe of these events in the last

100 yr was recorded in 1947 (Brázdil et al. 2016b this Special) with less pronounced episodes since then in 1953–1954, 1959, 1992, 2000, 2003, 2007 (Brázdil et al. 2015b) and most recently in 2011–2012 (Zahradníček et al. 2015) and 2015. Recent drought episodes after 2000 led to increased research efforts focusing on drought climatology, causes and impacts (Hlavinka et al. 2009, Škvarenina et al. 2009, Trnka et al. 2009, Brázdil et al. 2013, 2015b, Potop et al. 2014, Bochníček et al. 2015). In the case of Austria, drought studies have focused on alpine hydrology, drought impacts on agriculture and hydrological factors such as runoff and groundwater tables (Blaschke et al. 2011, Thaler et al. 2012, van Loon et al. 2015) but have not assessed the trends in drought indicators. In the Czech Republic, however, drought trends between 1961 and 2000 or 2010 have been evaluated in several studies (e.g. Trnka et al. 2009, Potop et al. 2014). By contrast, comprehensive studies of this type have not been conducted for Slovakia or Austria, and comparisons have not been made with neighboring countries using station data. Although large-scale studies covered the region in the past, they relied on a considerably smaller number of stations, and therefore have far lower resolution (Dai 2013, van der Schrier et al. 2013, Spinoni et al. 2014). This is the first drought-focused study that uses homogenized station data and the whole range of drought indices.

The main objectives of this study were to evaluate the trends in drought occurrence indicated by 4 drought indices during the 1961–2014 period, and to identify differences among individual areas, environmental zones and elevations in a selected part of Central Europe (the Czech Republic, Slovakia and northern Austria). First, an analysis of drought episodes between 1961 and 2014 was carried out together with a determination of the most drought-prone areas. This was followed by analysis of the trends toward increased dryness/wetness, and a comparison of differences in drought occurrence between the 1961–1990 and 1991–2014 periods. Finally, the regionalization of drought characteristics was analyzed.

2. AREA STUDIED AND DATA

The area studied consists of the territory of the Czech Republic, Slovakia and northern Austria. When the climate-driven environmental classification of Europe according to Metzger et al. (2005) is used, the study area is dominated by the Continental (CON) classification. Parts of this zone, and in particular
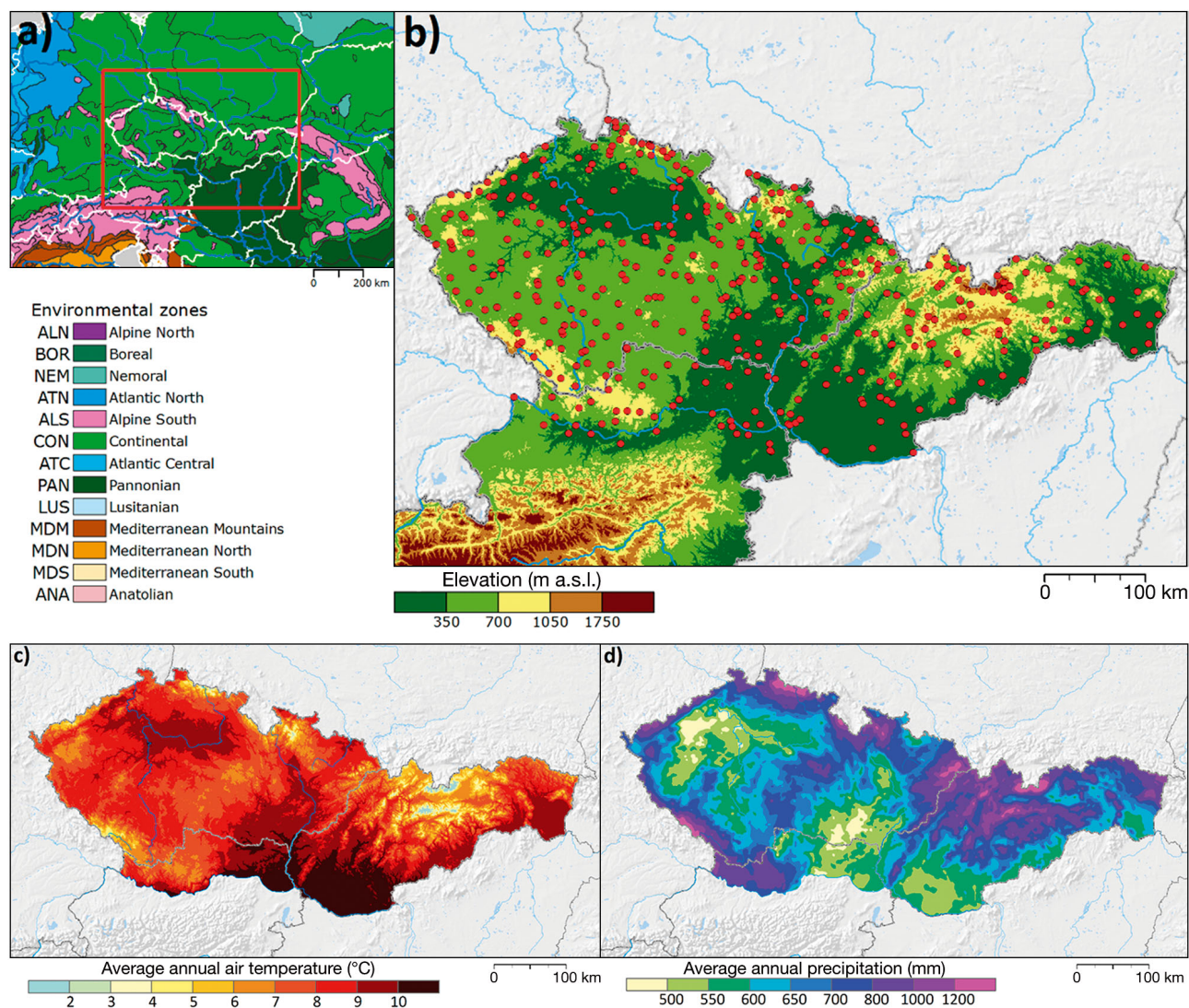
Fig. 1. (a) Overview of the study area with delimitation of environmental zones according to Metzger et al. (2005); (b) location of the climatological stations used in the study for Austria, Czech Republic and Slovakia; (c) mean annual temperature (°C) and (d) mean annual precipitation total (mm) for the study region during the 1981–2010 period

those in Pannonian environmental zone (PAN), are the most susceptible (in the study region) to drought. Higher elevations belong to the Alpine South zone (ALS) (Fig. 1a). The basic climatic patterns are documented in Fig. 1c–d, which shows mean annual temperatures and precipitation totals for the 1981–2010 period. Mean monthly temperatures are usually highest in July and lowest in January or February, with some changes in the temperature pattern in a west–east direction; summer has the highest and winter has the lowest seasonal precipitation totals.

The study area is well covered by climatological stations (Fig. 1b), representing various environmental zones (Fig. 1a), with elevations between 100 m

(Somotor, Slovakia) and 2634 m (Lomnický štít, Slovakia). The mean elevation of the stations is 457 m, which is close to the mean elevation of the region (452 m). A database of meteorological variables was produced by the Czech Hydrometeorological Institute, Slovak Hydrometeorological Institute in Bratislava, Central Institute for Meteorology and Geodynamics in Vienna, the Global Change Research Institute in Brno, University of Natural Resources and Life Sciences in Vienna and Mendel University in Brno as a part of the CECILIA FP6 project, followed by several national activities (www.drought.cz, https://ada.boku.ac.at/). The database covers 411 climatological stations and includes daily minimum and

maximum temperatures, sums of global radiation, precipitation totals, mean wind speeds and air humidity. The global radiation measurements, as a key input parameter in evapotranspiration calculations, were based partly on direct measurements by pyranometers (10 stations recording measurments from 1983 in the Czech Republic) and over 100 stations recording sunshine duration using heliographs during the 1961–2014 period. Based on previous studies (e.g. Trnka et al. 2005), the Angström-Prescott formula (Prescott 1940) was used to estimate daily global radiation.

All meteorological data were homogenized and checked for consistency using AnClim and ProClim software (Štěpánek et al. 2009, Brázdil et al. 2012). For calculation of areal means on a daily time step, maps were obtained using universal linear kriging interpolation, taking into account the influence of elevation (Šercl & Lett 2002). Local linear regression was applied; a diameter of 40 km was used for air temperature, global radiation, wind speed and air humidity, and a diameter of 20 km was used for precipitation. The so-called technical series of climatic variables (quality controlled, homogeneous and with filled gaps) were used as input for the interpolation (for more details see Štěpánek et al. 2011).

The Standardized Precipitation Index (SPI), Standardized Precipitation–Evapotranspiration Index (SPEI) and Palmer Drought Severity Index (PDSI) including its component Palmer Z-index (Z-index) were applied in this study as the most frequently used drought indicators. Algorithms for the calculation of the last 3 indices were upgraded to address their known caveats.

2.1. Standardized Precipitation Index (SPI)

The SPI is one of the most recent and widely accepted indicators used for drought evaluation at multiple time scales with either monthly or weekly precipitation data. Its calculation is based on the cumulative probability of a given precipitation event occurring at a given station (McKee et al. 1993).

When we analyze regions with different precipitation totals at individual stations but with similar annual patterns of rainfall distribution, then the McKee et al. (1993) SPI (further self-calibrated SPI, or scSPI) results will inevitably indicate a similar number of dry episodes. Although scSPI is of particular value in drought monitoring, its definition of drought as a deviation from the local mean restricts its use as a tool for regional classification in the climatology of

drought. This intrinsic property of the scSPI could be partially bypassed through evaluating those scSPI parameters that preserve their variability in space (e.g. Lloyd-Hughes & Saunders 2002, Sönmez et al. 2005). However, this approach comes up short in distinguishing subtle differences between various types of climatic regions over relatively small areas (or regions), as is the case in this study, and this is not very suitable for communication with stakeholders. Therefore, we used the 'relative SPI' (rSPI; Trnka et al. 2009). The rSPI calculation defines the parameters of the gamma distribution based on the dataset created by aggregating all monthly precipitation totals from the 411 stations in the 1961–1990 period. In the following step, the values of the rSPI relative to the reference distribution function were derived for each site (for the use of relative indices, see Dubrovský et al. 2009 and Trnka et al. 2009).

2.2. Palmer Drought Severity Index (PDSI) and Palmer Z-index

The PDSI is one of the most frequently used indices for quantifying drought throughout the world (van der Schrier et al. 2006, Büntgen et al. 2011b, Dai 2013, Cook et al. 2015, Feng et al. 2016). A comprehensive overview of the necessary calculation procedures for PDSI is given by Palmer (1965), Alley (1984) and van der Schrier et al. (2006, 2007). This study uses the self-calibrated version of the index (scPDSI) according to Wells et al. (2004). In general, the index is based on the supply-and-demand concept of a water balance equation, and thus incorporates antecedent precipitation, moisture supply and demand at the surface as calculated according to the Thornthwaite (1948) potential evapotranspiration (PET) method. This empirical PET method is very sensitive to temperature changes and may lead to greater negative PDSI values (Sheffield et al. 2012). Therefore, we estimated PET using the Penman-Monteith method (Allen et al. 1998), which accounts for the impacts of temperature, solar radiation, wind speed and relative humidity on PET. To address other frequently listed shortcomings of the PDSI, such as the lack of a snow cover module, we employed a daily snow cover model to account for the form of precipitation (Trnka et al. 2010).

According to Trnka et al. (2009), the 'relative PDSI' (rPDSI) and 'relative Z-index' (rZ-index) better describe the drought climatology of the region by estimating drought intensity through modeled soil moisture status. The empirical coefficients of both indices

(K value) were based on 12 330 yr of data (i.e. set of all monthly observed values from 411 stations covering the whole region of interest for the 1961–1990 period). In the first step, departures from normal soil moisture levels were calculated for each station, and the resulting rZ-index value enabled identification of differences between individual sites. Subsequently, the rPDSI value was determined using the same procedure as used for the PDSI. This approach allowed a comparison of the soil moisture anomaly of each month with the distribution that served as a representation of the overall country climatic conditions. According to the rZ-index (rPDSI), a drought episode was defined as a continuous period of index values below −0.25 (−1.0 for PDSI) that drop below −1.25 (−2.0 for PDSI) at least once during the episode; individual categories were assessed according to Table 1.

The maximum soil water holding capacity (MSWC) is needed to calculate the PDSI. For this study, a constant MSWC of 260 mm m^{-1} depth was used as this represents good quality soil. While such a value is not realistic at higher elevations or for sandy soils in lowlands, the effect on the overall PDSI values in this region is relatively small (e.g. Büntgen et al. 2011a).

2.3. Standardized Precipitation-Evapotranspiration Index (SPEI)

The multi-scalar character of the SPEI enables its use in different scientific disciplines to detect, monitor and analyze droughts (Vicente-Serrano et al. 2010). Similar to the scPDSI and the scSPI, the SPEI can measure drought severity according to its intensity and duration and can identify the onset and the end of drought episodes. The SPEI uses the monthly differences between precipitation and PET as a measure of a simple climatic water balance. The calculation of PET in this paper was performed using the Penman-Monteith method (Allen et al. 1998) and accounted for the snow cover influence using the Trnka et al. (2010) approach. Similar to previous indices, the 'relative SPEI' (rSPEI) was calculated for purposes of spatial analysis. The dataset created by aggregating all monthly precipitation and evapotranspiration totals from the 411 stations in the 1961–1990 period was used to parameterize a single reference distribution function for the whole territory.

2.4. Integrated Climatological Drought Indicator (ICDI)

An Integrated Climatological Drought Indicator (ICDI), conceptually proposed by Trnka et al. (2009), can be used to better communicate results to stakeholders and policy makers. Its main purpose is to provide a relatively simple but robust measure of the relative dryness of a given site in relation to the region of interest. This indicator accounts for the percentage of months that fall in a drought spell according to rSPI, rZ-index, rPDSI and rSPEI during the evaluated time period. Combining both the number of drought events and their duration, ICDI allows visualization of drought risk over the area utilizing a single map. The major shortfall of this approach is that it does not fully account for the intensity of the individual drought events. However, this was dealt with by evaluating individual time series in a separate exercise (see Fig. 2). The ICDI was based on the mean percentage of months in a drought spell as defined in Table 1. We used the 1, 3 and 12 mo rSPI, 1, 3 and 12 mo rSPEI, rZ-index, Z-index and PDSI. All indicators had the same weights. The ICDI takes into account not only indicators based on precipitation deficit (i.e. rSPI) but also includes the effect of evaporation demand (rSPEI, rZ-index and rPDSI) and soil properties (rZ-index or rPDSI).

In drought trend studies, many researchers prefer monthly data for various reasons, including better availability (Lloyd-Hughes & Saunders 2002, Dai et al. 2004, van der Schrier et al. 2007, Feng et al. 2016) and lower sensitivity to observational errors (Viney & Bates 2004). This study addresses drought in time scales ranging from 1 to 12 mo, although we are aware of the fact that shorter time steps would be needed to study certain as-

Table 1. Standardized Precipitation Index (SPI), Standardized Precipitation–Evapotranspiration Index (SPEI), Palmer Z-index (Z-index) and Palmer Drought Severity Index (PDSI) categories according to Heim (2002) and Vicente-Serrano et al. (2010)

SPI	SPEI	Z-index	PDSI	Drought index category
≥2.00	≥2.00	≥3.50	≥4.00	Extremely moist
1.50 to 1.99	1.50 to 1.99	2.5 to 3.49	3.00 to 3.99	Very moist
1.00 to 1.49	1.00 to 1.49	1.00 to 2.49	2.00 to 2.99	Moderately moist
−0.99 to 0.99	−0.99 to 0.99	−1.24 to 0.99	−1.99 to 1.99	Normal range
−1.00 to −1.49	−1.00 to −1.49	−1.25 to −1.99	−2.00 to −2.99	Moderately dry
−1.50 to −1.99	−1.50 to −1.99	−2.00 to −2.74	−3.00 to −3.99	Severely dry
≤−2.00	≤−2.00	≤−2.75	≤−4.00	Extremely dry

pects of drought impacts on agriculture, and longer time steps should be used when hydrological droughts are analyzed. The 1 mo SPI, SPEI and Z-index values are referred to as short-term drought indicators, the 3 mo SPI and SPEI as medium-term drought indicators and the 12 mo SPI, SPEI and PDSI as long-term drought indicators. Tables 1 & 2 show the drought categories indicated by the indices as well as the definition of a drought episode used in this study.

Monthly series of the 1, 3, 6 and 12 mo SPI, SPEI and the PDSI, and Z-index from 1961–2014 were tested for significant trends. We applied the non-parametric Mann-Kendall trend test (Kendall 1990) and considered a trend as significant if the confidence level was 95% or higher. In the case of the trend analysis, the self-calibrated methods of index calculations (rather than their relative versions) were used. To avoid any existing autocorrelation between consecutive drought indices, the trends were evaluated for each month separately. Under these circumstances, all values in each of 12 series can be considered independent. For every station, we evaluated the number of months with statistically significant trends toward drier/wetter conditions. For stations without statistically significant trends, we examined the slope of the regression line.

3. RESULTS

3.1. Dry spells in the 1961–2014 period

Due to the relatively large number of stations and good spatial coverage (Fig. 1b), we selected the percentage of stations in severe to extreme drought (Table 1) as an indicator of the spatial extent of the droughts. As observed in Fig. 2, the number and spatial extent of short-term drought events (Z-index or 3 mo scSPI and scSPEI) were significantly higher than those of long-term drought spells (12 mo scSPEI and scPDSI). According to the Z-index, >80% of the stations were affected by a severe or extreme drought in 1976, 1983, 2003 and 2007. In particular,

the drought of summer 2003 was unique — three-quarters of the stations were hit by extreme drought. Nine short-term drought spells affecting >60% of the stations were detected according to the scZ-index in the summer half-year. When medium-term drought (3 mo) was considered, 5 episodes (1964, 1972–1973, 2000, 2003 and 2012) crossed the severe drought threshold at >60% of the stations. On occasion (such as in 1972 or 2003), a short-term event was a precursor to a long-term drought episode, which led to hydrological impacts (low reservoir levels, limited stream flows, depletion of groundwater).

While the results obtained using the scZ-index were rather similar to those of the 3 mo SPEI, the percentage of stations in a drought according to the scPDSI values correlated well with the 12 mo SPEI. As Fig. 2 shows, there were several major drought spells during 1961–2014; the longest occurred in 1990–1995 and the most intensive in terms of number of stations affected occurred in 2003.

3.2. Delimitation of drought-prone regions

Based on the rSPI, rSPEI, rZ-index and rPDSI, the highest number of drought events occurred in the north-western, south-central and extreme south-eastern parts of the region. The dry episodes in these areas were distinguished by their substantially higher intensity and longer duration, exceeding 4 mo on average. Dry episodes were rarely observed in the mountainous regions along the northern, north-western, eastern and south-western borders of the Czech Republic, north-central part of Slovakia and the highlands located in the center of the Czech Republic and Upper Austria. Nevertheless, the occurrence of short-term drought episodes cannot be excluded even at these locations, which are generally characterized by elevations >800 m with mean annual precipitation totals that exceed 800 mm. When they do occur, these episodes tend to be short, with rSPI values rarely reaching below −2.0. Interestingly, lowland stations in the north-eastern region of the Czech

Table 2. Definition of drought episodes according to individual indices. SPI: Standardized Precipitation Index; SPEI: Standardized Precipitation–Evapotranspiration Index; Z-index: Palmer Z-index; PDSI: Palmer Drought Severity Index

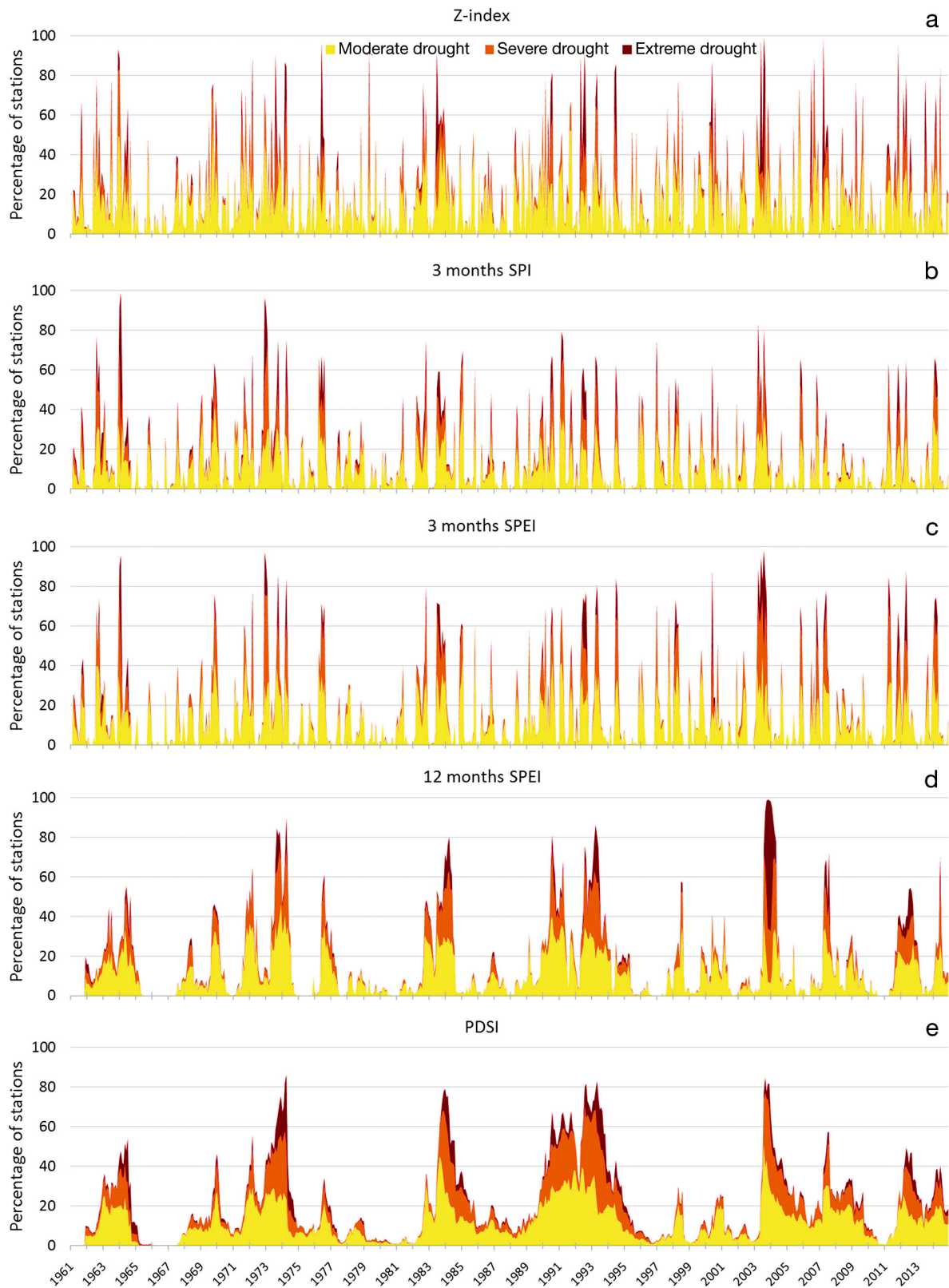| Stages of drought episodes	SPI	SPEI	Z-index	PDSI
Start	Drops below −1.0	Drops below −1.0	Drops below −1.25	Drops below −2.0
Minimum value	At least 1 mo below −1.5	At least 1 mo below −1.5	At least 1 mo below −2.0	At least 1 mo below −3.0
End	Rises above 0.0	Rises above 0.0	Rises above 0.0	Rises above 0.0

Fig. 2. Percentage of 411 climatological stations with moderate, severe and extreme droughts during the 1961–2014 period according to the (a) self-calibrated Palmer Z-index (scZ-index), (b) 3 mo self-calibrated Standardized Precipitation Index (scSPI), (c) 3 mo self-calibrated Standardized Precipitation–Evapotranspiration Index (scSPEI), (d) 12 mo scSPEI, and (e) self-calibrated Palmer Drought Severity Index (scPDSI)

Republic also have a negligible probability of drought occurrence (Fig. 3). The decisive factor contributing to the lower drought risk in this area is the enhanced precipitation, which is approximately 60% higher on average compared with the corresponding lowland areas located in the south-eastern part of the country (Tolasz et al. 2007). This can be explained by distinctly different precipitation regimes due to a higher frequency of slowly moving Mediterranean cyclones in the northeastern part of the Czech Republic (Hanslian et al. 2000, Kyselý et al. 2007). However, it is precisely in this region in which the 2015 drought was the longest and most intense (www.intersucho.cz).

Further, we also analyzed the 3 and 12 mo rSPI and rSPEI values to evaluate the respective medium- and long-term drought episodes. Although their absolute number decreased with increasing aggregation, these episodes tended to be much longer and showed a much higher level of persistence, as McKee et al. (1993) noted in their original paper. For example, the percentage of months affected by drought according to the 3 mo rSPI reached 70% in the Pannonian area and the Elbe River lowland, while episodes of short-term droughts only accounted for half of the months in the same areas. The differences between the lowland areas and mountains were enhanced by applying the 3 and especially the 12 mo rSPI indices. As several consecutive months with low precipitation

are highly unlikely in the mountains, the percentage of time that mountain stations were in a drought according the 12 mo rSPI was negligible (Table 3).

From a climatological point of view, there are several 'epicenters' of drought-prone regions according to the ICDI (Fig. 3). The largest continuous area with a high risk of drought occurrence (>60% of months with dry spells) was observed in the southeastern part of the Czech Republic and across Lower Austria. The second major area extended across south-western Slovakia (including Žitný ostrov Island). Secondary 'epicenters' were located in the north-west (the Elbe River lowland and the lee side of the Krušné hory Mts.) and south-eastern Slovakia. In contrast, the mountain ranges on the Czech border with Germany and Poland, as well as the Bohemian-Moravian Highlands in the center of the Czech Republic, and mountainous regions in the central part of Slovakia and Upper Austria were only rarely affected. Fig. 3 further indicates that the highest drought risk appears on the alluvial soils around the Danube, lower Morava and Tisza rivers, which roughly corresponds to the Pannonian zone (Table 3). The drought susceptibility in these regions is due to the relatively low precipitation and high potential evapotranspiration, which leads to an insufficient accumulation of moisture in the soil profile, particularly during the summer half-year. The local effects of drought depend on the soils. In the case of alluvial
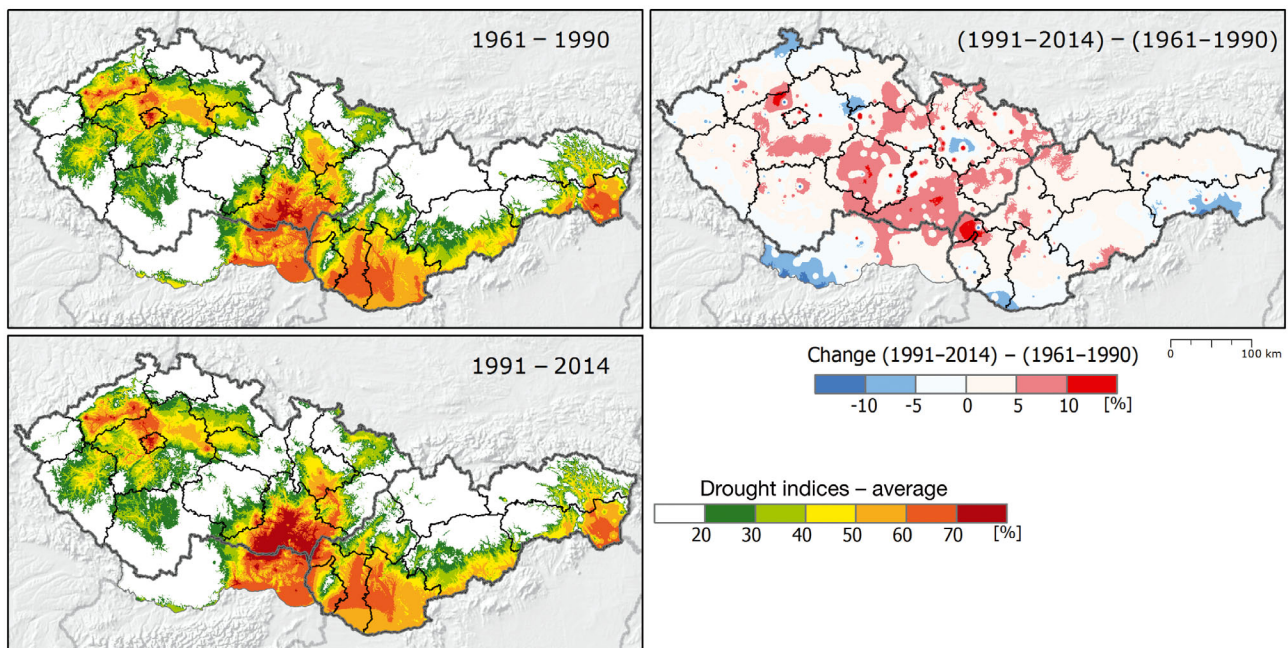

Fig. 3. Percentage of time of drought episodes according to the Integrated Climatological Drought Indicator (ICDI) during the 1961–1990 and 1991–2014 periods as well as the difference between both periods

Table 3. Selected drought characteristics based on the 1 and 3 mo relative Standardized Precipitation–Evapotranspiration Index (rSPEI), relative Palmer Z-index (rZ-index) and relative Palmer Drought Severity Index (rPDSI) for groups of stations divided according to their elevation and environmental zone (according to Metzger et al. 2005). PAN: Pannonian zone; CON: Continental zone; ALS: Alpine South zone

| | No. of stations | Mean elevation (m) | Mean annual temperature (°C) | Mean annual precipitation (mm) | Percentage of time in the drought episode during 1961–1990 | | | | Change in time (%) in the drought episode in 1991–2014 compared to 1961–1990 | | | |
					1 mo rSPEI	3 mo rSPEI	rZ-index	rPDSI	1 mo rSPEI	3 mo rSPEI	rZ-index	rPDSI
Elevation (m a.s.l.)												
90–200	47	148	9.8	563	43.6	55.8	65.1	68.0	+1.3	+3.9	−1	+4.7
200–400	157	296	8.8	640	21.4	28.6	41.3	28.8	+5.1	+4.8	+3.7	+7.3
400–600	124	495	7.7	695	9.5	11.5	23.7	17.9	+4.4	+2.8	+3.1	+2.6
600–1000	65	757	6.3	866	4.5	4.2	9.6	1.8	+1.5	−0.2	+1.6	−0.4
>1000	18	1319	3.1	1160	1.9	0.6	2.0	0.0	+0.1	+0.1	+0.4	0
All stations	411	457	7.9	706	16.8	21.5	32.0	21.5	+3.7	+3.1	+2.5	+4
Environmental zone												
PAN	37	179	10.0	551	51.0	63.2	71.0	77.9	+0.4	+3.8	−1.7	+3.1
CON	312	440	8.0	689	15.2	19.9	31.6	18.6	+4.6	+3.8	+3.4	+5.1
ALS	59	662	6.5	864	4.8	4.9	11.3	2.5	+0.9	−1	+0.5	−1.1
All stations	411	457	7.9	706	16.8	21.5	32.0	21.5	+3.7	+3.1	+2.5	+4

soils, the impacts are frequently mitigated by the high water-holding capacity of these deep soils as well as by capillary water rise at sites with shallow underground water tables (e.g. Žitný ostrov Island in Slovakia).

3.3. Trend analysis

Analysis of the trends in annual precipitation totals recorded at the 411 stations showed statistically significant changes in <20% of the stations (with domination of wetting trends) during the 1961–2014 period. Similarly, the long-term scSPI series for individual stations demonstrated patterns toward a wetter climate for almost one-quarter of the stations. Positive and highly significant trends in mean air temperatures, especially associated with the unusually warm period of 1991–2014, were found for the majority of the 411 stations.

As a direct result of increasing temperature and no change in precipitation, the monthly series of the scZ-index, scPDSI and scSPEI showed decreasing trends, indicating more frequent and/or severe droughts (Table 4). Overall, 36% (34%) of stations showed statistically significant negative trends (increased dryness) in at least 1 month according to the scZ-index (SPEI), compared to 8% (9%), with a positive trend in the summer half-year (Table 4, Fig. 4).

By contrast, wetting trends prevailed in the winter half-year (Fig. 5). The remaining stations did not show any statistically significant trends; however, a large number of stations inclined toward lower scZ-index and SPEI values over time (Figs. 4 & 5). Trends were also pronounced in the scPDSI and 12 mo SPEI, characterizing long-term drought spells compared with shorter spells identified with the scZ-index and 1 mo SPEI (Figs. 4 & 5). Statistically significant trends toward negative scPDSI values in the summer half-year were detected for 35% of the stations, most of which exhibited a significant decrease in PDSI for 3 or more months. Only 7% of the stations showed the opposite tendency. During the winter half-year, 26% of stations showed a negative trend (increased dryness) and 11% a positive trend (increased wetness). Out of the almost 60% of stations with no statistically significant trend, more than two-thirds showed a decrease in scPDSI values rather than an increase or no change. Similar results were found for the 12 mo scSPEI, with 14% of the stations showing a negative trend and 5% a positive trend. However, in the case of the winter half-year trends of 1 and 3 mo scSPEI and scZ-index, the prevalence of stations with a tendency toward wetter conditions is obvious.

As Fig. 4 shows for the summer half-year, the proportions of stations with trends toward higher dryness are much greater than those toward higher wetness. This was also valid for the winter half-year (Fig. 5), particularly for scPDSI and the 12 mo scSPEI. The prevalent trends for long-term drought indicators suggest that the summer half-year drying was not fully compensated by the wetting trends in the winter half-year.

Table 4. Percentage of stations with statistically significant trends toward increased dryness/wetness for at least 1 mo in the summer or winter half-year during the 1961–2014 period. Stations are divided according to their elevation and environmental zones. PAN: Pannonian zone; CON: Continental zone; ALS: Alpine South zone. scSPI: self-calibrated Standardized Precipitation Index; scSPEI: self-calibrated Standardized Precipitation–Evapotranspiration Index; scZ-index: self-calibrated Palmer Z-index; scPDSI: self-calibrated Palmer Drought Severity Index

	No. of stations	Mean elevation (m)	Percentage of stations with significant **drying**/wetting trend							
			1 mo scSPI	1 mo scSPEI	scZ-index	3 mo scSPI	3 mo scSPEI	12 mo scSPI	12 mo scSPEI	scPDSI index
Summer half year										
Elevation (m a.s.l.)										
90–200	47	148	9/45	13/6	13/6	6/36	36/0	0/6	26/0	38/0
200–400	157	296	18/34	34/8	39/7	18/29	51/4	2/15	22/1	48/3
400–600	124	495	26/40	44/6	44/5	14/44	51/6	2/31	10/3	31/6
600–1000	65	757	25/34	37/15	38/11	22/34	42/8	2/35	8/11	17/15
>1000	18	1319	0/44	11/28	17/28	6/67	11/61	0/56	0/44	6/44
Environmental zone										
PAN	37	179	0/49	3/5	11/5	3/51	41/0	0/3	35/0	41/0
CON	312	440	18/35	35/8	37/7	15/34	46/6	2/24	16/3	38/6
ALS	59	662	42/46	51/15	51/14	25/41	53/15	0/34	0/15	20/14
All stations	411	457	20/37	34/9	36/8	16/37	46/7	1/24	15/5	35/7
Winter half year										
Elevation (m a.s.l.)										
90–200	47	148	6/32	19/19	13/6	2/11	2/4	0/11	23/0	26/0
200–400	157	296	11/39	18/30	20/17	3/17	6/6	2/13	21/2	38/4
400–600	124	495	2/39	5/24	6/19	2/31	2/8	2/29	8/3	22/10
600–1000	65	757	2/48	5/46	5/46	5/51	6/37	2/31	6/11	12/29
>1000	18	1319	0/83	6/67	11/67	0/83	0/78	0/56	0/44	6/50
Environmental zone										
PAN	37	179	8/27	24/16	16/0	8/0	8/0	0/5	30/0	35/0
CON	312	440	6/43	12/30	14/21	2/28	4/11	2/22	15/3	29/9
ALS	59	662	2/42	2/44	2/47	0/47	0/37	0/31	0/15	10/25
All stations	411	457	6/42	11/31	12/23	2/29	4/15	1/22	14/5	26/11

3.4. Comparison of droughts in the 1961–1990 and 1991–2014 periods

Drying trends inevitably also affect the duration of droughts, as documented in Table 3. There was a tendency toward an increased time during which the stations were influenced by drought episodes in the 1991–2014 period compared with 1961–1990. While the change was not major, the tendency was fairly robust. An increased occurrence of the most extreme drought categories can be seen as subtle shift in the occurrence of the most extreme categories (Fig. 6). We noted a slight increase across all drought indicators with respect to the frequency of the severe and extreme drought categories, as these events occurred more frequently and had a longer duration in 1991–2014. Interestingly, there was no decrease in number of extremely wet events, especially at the 1 and 3 mo scales. The ICDI values in Fig. 3 correspond to the shifts noted above. The most obvious increase in drought frequency was evident in the south-central part of the study region, with subtle changes in southern Slovakia. In the eastern and north-western areas, there were subtle changes in drought hotspots; in some cases, even very small reductions in drought frequency were recorded.

3.5. Regionalization of droughts

Table 3 shows distinct differences in the frequency of drought indicated by the relative drought indices between individual elevations and environmental zones. The greatest shift toward more frequent drought occurred between elevations of 200 and 600 m and in the CON zone. In addition, the PAN zone shifted toward higher drought occurrence according to the 3 mo SPEI and rPDSI, but to a lesser extent. On the other hand, there was an obvious tendency toward wetter conditions, especially in the winter half-year for stations located at elevations above 1000 m and in the ALS zone.

This can be partly explained by the higher proportion of liquid precipitation and an overall increase in
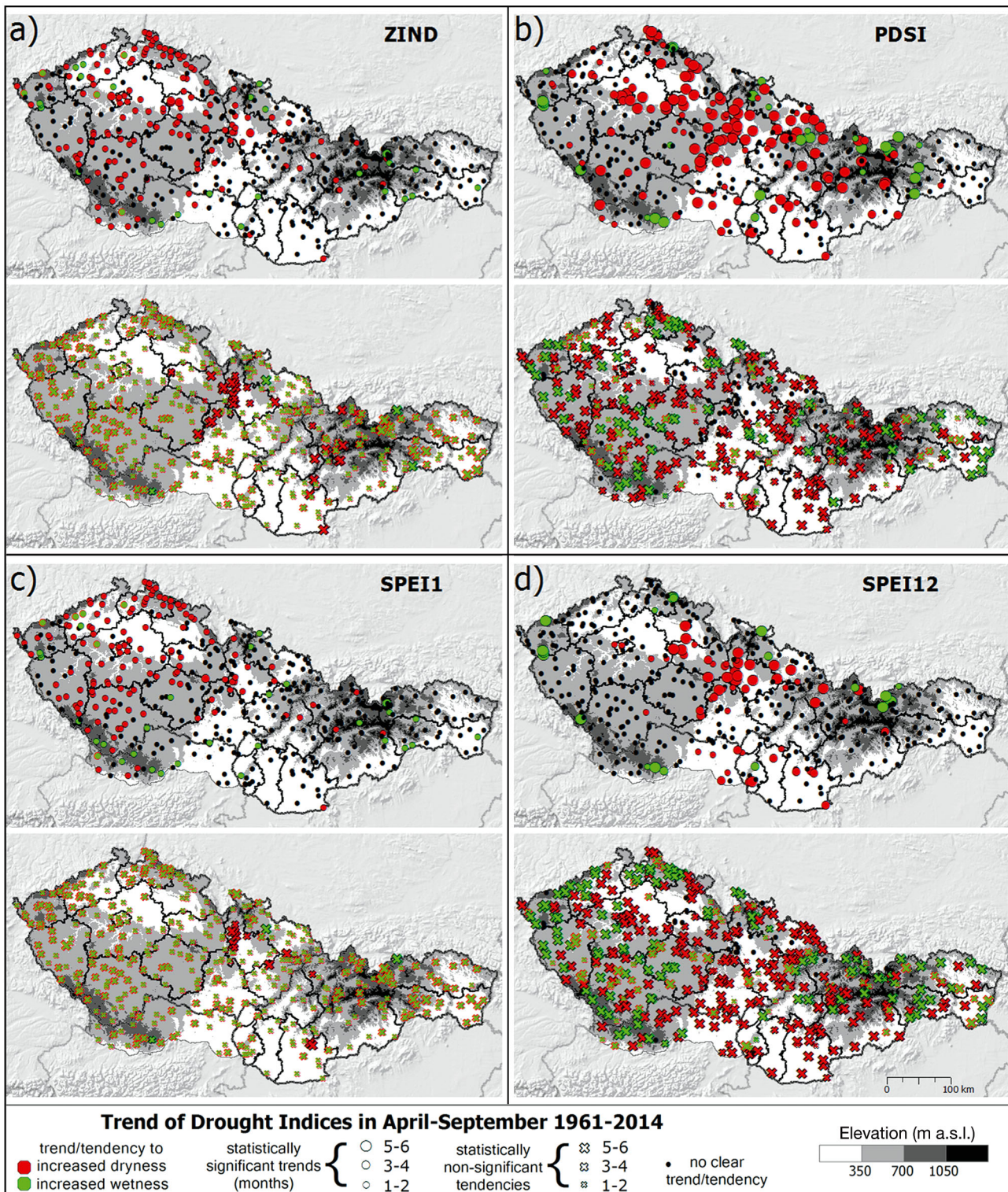
Fig. 4. Number of months within the summer half-year (April–September) with positive and negative significant trends (α = 0.05, upper panels) and non-significant tendencies (lower panels) for the (a) self-calibrated Palmer Z-index (scZ-index), (b) self-calibrated Palmer Drought Severity Index (scPDSI), (c) 1 mo self-calibrated Standardized Precipitation–Evapotranspiration Index (scSPEI), and (d) 12 mo scSPEI. Evaluations of trends/tendencies were carried out individually for each month in the 1961–2014 period. Green symbol with red outline: both types of trends/tendencies occurred. Note: negative trends/tendencies signal increasing drought duration/intensity
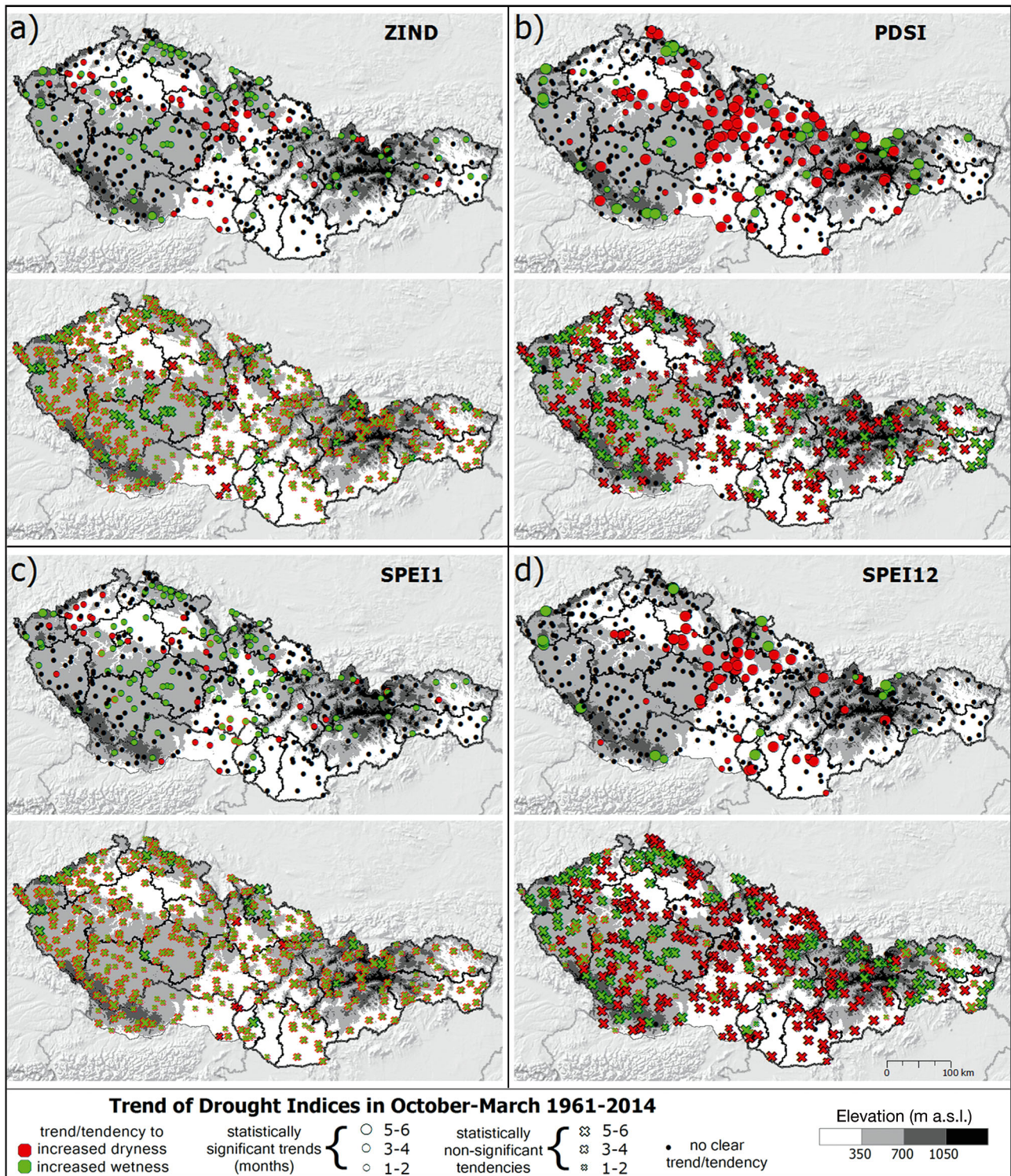
Fig. 5. As in Fig. 4 for the number of months in the winter half-year (October–March) with positive and negative significant trends

precipitation totals that leads to higher availability of water, and results in the more positive (i.e. 'wetter') index values. However, this also means that water that would be released later in the spring during snow-melt reaches streams and soil earlier. This will change the pronounced seasonality in runoff in the Alpine zone (Fürst et al. 2008, Blaschke et al. 2011, APCC 2014). At the same time, almost the opposite
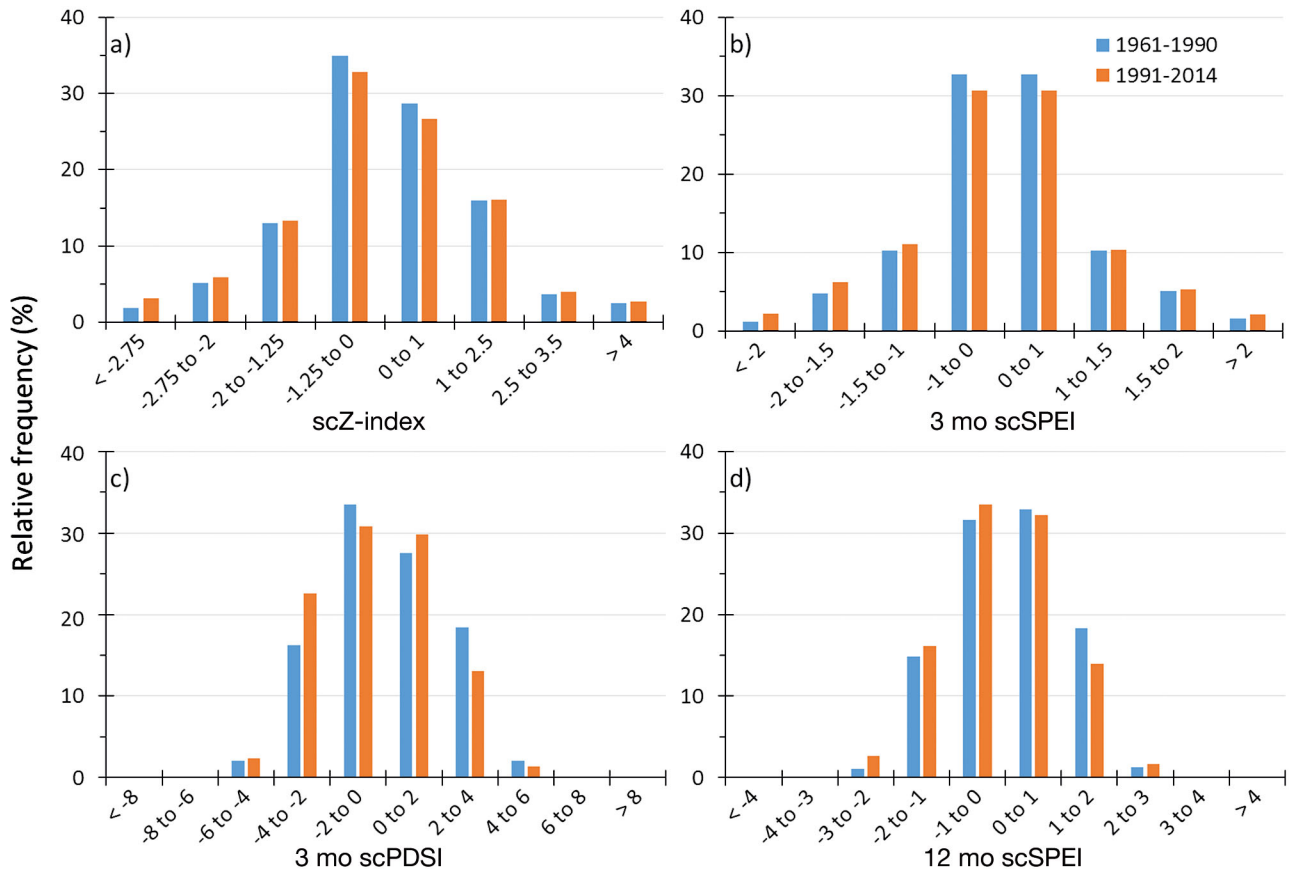
Fig. 6. Comparison of relative frequencies of drought indices for the 1961–1990 and 1991–2014 periods calculated for 411 climatological stations based on the (a) self-calibrated Palmer Z-index (scZ-index), (b) 3 mo self-calibrated Standardized Precipitation–Evapotranspiration Index (scSPEI), (c) self-calibrated Palmer Drought Severity Index (scPDSI), and (d) 12 mo scSPEI. Categories are based on Table 1

situation occurred in the summer half-year in the warmest Pannonian zone and at elevations below 200 m, and to some extent at elevations between 201–600 m or in the CON zone. This means that while dry regions became increasingly drier, the stations at higher elevations showed trends toward increased wetness; however, this occurred at the expense of snow cover and therefore lowered the potential water flow at lower elevations during the season.

4. DISCUSSION

4.1. Potential evapotranspiration and baseline period

Some drought indices such as the SPI are based on precipitation alone and only provide a measure of water supply. They are very useful as a measure of precipitation deficit or meteorological drought (Spinoni et al. 2015), but are limited because they do not address the water demand side of the water balance. The concept of the SPI was extended to SPEI, which is a product that includes both precipitation and PET data. The PDSI takes this one step further by accounting for the balance of precipitation, evapotranspiration and runoff and has the ability to incorporate local soil and possibly vegetation properties, making it a fairly comprehensive and flexible index of relative drought (Trenberth et al. 2014). Both SPEI and PDSI use the Thornthwaite (1948) method to account for evapotranspiration effects. This approach considers only monthly precipitation and temperature, and has the major advantage of being easily calculated because of the availability of these data for most global land areas. The disadvantage is that it cannot account for changes in solar and infrared radiation, humidity and wind speed, which we discuss below. A more realistic and complex approach to estimating PET in the PDSI is the method outlined by Penman in 1948 and modified by Monteith to yield the Penman-Monteith formulation, which incorpo-

rates the effects of wind and humidity, plus solar and longwave radiation.

In global or large-scale studies, most of the data needed to estimate PET through the Penman-Monteith approach are not readily available (Trenberth et al. 2014, Spinoni et al. 2015) or generally suffer from temporal and spatial inhomogeneity. However, for Central Europe, the datasets were properly homogenized and can be considered high-quality records. Fig. 7 shows that there are indeed very small differences between the SPEI using the Thornthwaite and Penman-Monteith algorithms, while the difference seems to be higher for different versions of PDSI. The higher sensitivity of the PDSI to different methods of the Penman-Monteith calculation stems from the way in which the drought/wet transition probabilities

are calculated; hence, a small difference in the PET estimate might have significant consequences (Palmer 1965).

Another important issue that has emerged in recent research (Sheffield et al. 2012, Trenberth et al. 2014) is the choice of the baseline period to define and calibrate the drought categories. Sheffield et al. (2012) and Spinoni et al. (2015) used a baseline period of 1950–2008 and 1951–2010, respectively, while Dai (2013) used 1950–1979, which was globally relatively wet. Obviously, such selection influences the results (Trenberth et al. 2014). The ideal baseline period should sample natural variability fully, i.e. longer records are preferable. However, there is also a problem in using a more recent baseline period (e.g. 1951–2010) because the effects of recent anthro-
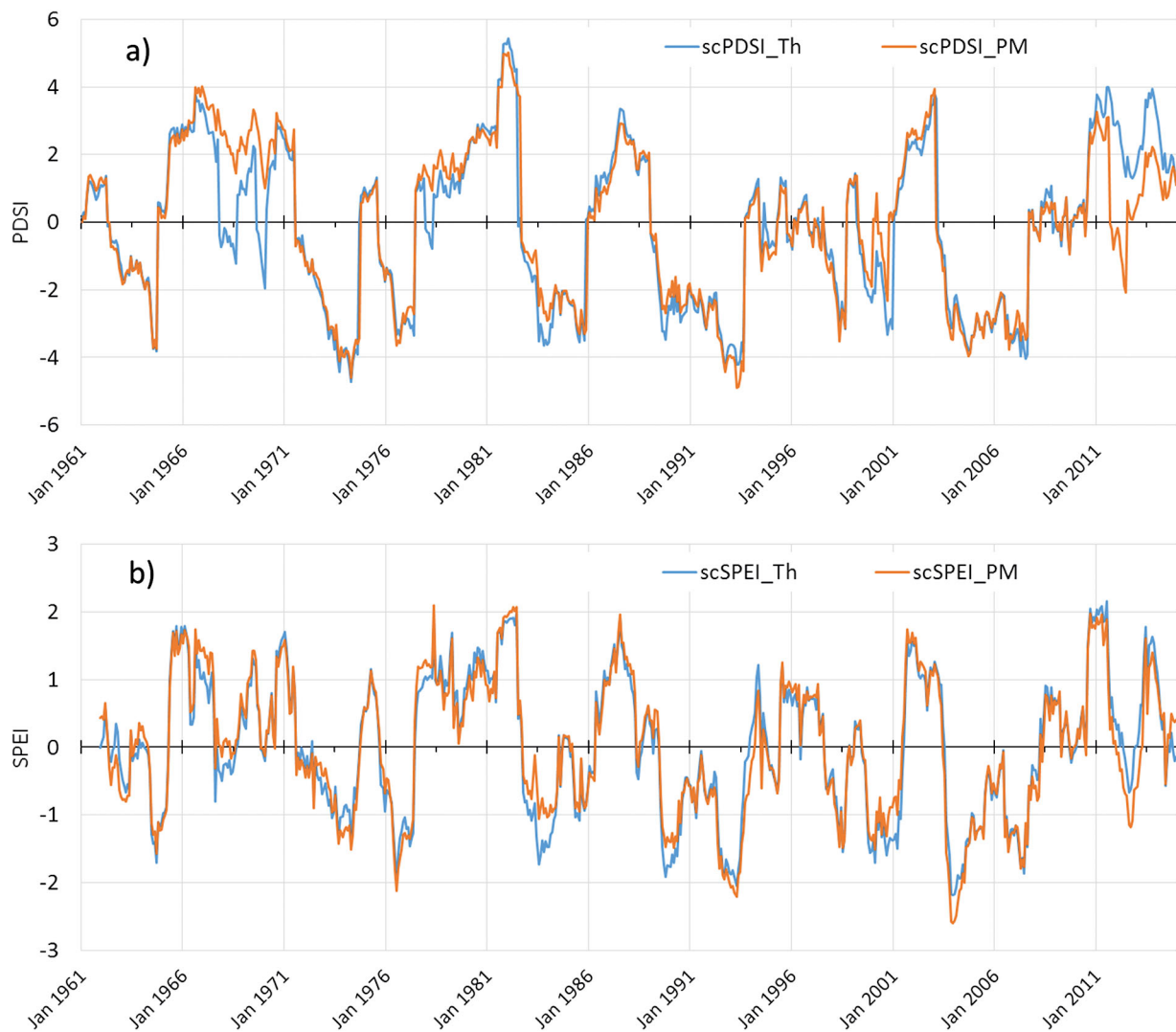

Fig. 7. Fluctuations in the (a) self-calibrated Palmer Drought Severity Index (scPDSI) and (b) self-calibrated 12 mo Standardized Precipitation–Evapotranspiration Index (scSPEI) series calculated for the Doksany station (Czech Republic) for the 1961–2014 period using the Thornthwaite (Th) and Penman-Monteith (PM) methods

pogenic forcings will be included. This alters the range of observed variability against which the long-term variations that characterize changes are scaled. Hence, it greatly reduces any prospects of identifying a climate change signal in the results of the analysis. Therefore, we selected 1961–1990 as the calibration period. Within this period, both extremely dry and wet episodes occurred (cf. Figs. 2 & 7).

4.2. Regional and large-scale context

The results obtained can be compared with continental-scale studies. Dai et al. (2004) and Dai (2013) reported the existence of a notable drying trend since the beginning of the 20th century throughout Europe that was linked to increasing air temperatures. Other studies, using a different dataset with a higher spatial resolution (0.5° grid), reported either strong or very strong drying trends for the area corresponding to our study (i.e. 48–51° N and 13–23° E). This includes the PDSI-based paper by van der Schrier et al. (2006) and more recent global studies by Sheffield et al. (2012) and van der Schrier et al. (2013). Spinoni et al. (2014), using precipitation-based SPI, showed a statistically significant tendency toward a higher number of droughts in the east of the Czech Republic, but this was not confirmed by our SPI station trends.

Brázdil & Kirchner (2007) evaluated scPDSI trends for stations within the Czech Republic for the 1850–2003 period. They reported a statistically significant trend toward lower PDSI with value of −0.1 decade^{-1}. The study by Brázdil et al. (2015a) for the 1805–2012 period showed an increase in spring–summer droughts (based on SPEI, Z-index and PDSI) and revealed the importance of the North Atlantic Oscillation phase and the aggregate effect of anthropogenic forcing (driven largely by increases in CO_2 concentration) on the frequency and severity of droughts. The longest drought reconstruction available for the region so far covers the 1501–2015 period (Brázdil et al. 2016a this Special). While individual drought episodes in recent decades have not reached the magnitudes of the most pronounced droughts, such as those of the 1720s, this drought reconstruction shows that a slow but continuous and robust drying has occurred since the late 19th century. More recent periods evaluated in different parts of the region also showed a consistent prevalence of drying trends over wetting tendencies during the past 50 yr in the Czech Republic (Brázdil et al. 2009a, Trnka et al. 2009, 2015, Potop et al. 2014). This corresponds

with the results of the detailed analysis of air temperature series performed by Květoň (2001), Huth & Pokorná (2005), Chládová et al. (2007) and Brázdil et al. (2009b) as well as the results obtained in the adjacent areas of Poland (Degirmendžič et al. 2004) and the Alps (Casty et al. 2005).

Furthermore, results for Slovakia (Labudová et al. 2015a, 2015b) indicate prevailing drying tendencies in the lowlands and surrounding lower parts of the territory. These drying tendencies are not triggered by the precipitation decline but by increasing temperatures enhancing evapotranspiration (Labudová et al. 2015a). This agrees well with previous papers published by Melo et al. (2007) and Pecho et al. (2008), which indicated such drying trends in earlier periods. In Austria, climatological research revealed detailed spatial-temporal trends by establishing long-term homogenized datasets such as HISTALP (Auer et al. 2005, Böhm 2006). No general precipitation trends can be found for the whole of Austria. However, due to the important influence of the Alpine ridge, Austria has to be divided into 3 different precipitation regions (Matulla et al. 2003). The most drought-prone region occurs in the northeastern part of Austria and is highly correlated with patterns in the neighboring Czech territory, as confirmed in this study. Similar to Austria, analysis of drought in Saxony using the decile method (Hänsel 2014) for the period 1901–2010 showed some drying tendency, but only in warm half-years, which waned in recent decades.

5. CONCLUDING REMARKS

Our analysis of a selected part of Central Europe showed that the most drought-prone region is north of the Danube River, including the junction of the borders of Austria, the Czech Republic and Slovakia. A second prominent region includes the north-western Czech Republic around the Elbe River and the third region is the south-eastern corner of Slovakia. These areas, mostly belonging to the PAN environmental zone, have shown increases in long-term drought occurrence. Trend analysis indicates that shifts in drought severity during the 1961–2014 period are not driven by a decrease in precipitation but rather by increased evaporation demand towards the end of the 20th century and in the early 21st century. The indicators that consider both precipitation and evaporative demand, i.e. SPEI, PDSI, Z-index of the atmosphere (or soil moisture), confirm strong trends toward increased dryness in the monthly and

long-term water balance deficits at many stations. This was driven not only by increasing temperatures but also by decreasing relative air humidity and increasing solar radiation in some months (Trnka et al. 2015). Moreover, most negative drying trends were found at lower elevations where the impacts on agriculture and forestry also tended to be the most intense. A significantly smaller number of stations in the area studied indicated that the conditions became wetter.

While the detected trends are not uniform, they strongly indicate tendencies toward increased dryness across the 3 countries. In fact, this agrees well with analyses based on documentary and/or tree ring data (Büntgen et al. 2011a, Dobrovolný et al. 2015, Brázdil et al. 2016a), and shows that the expected drying of the analyzed region — shown by the majority of the global and regional circulation models — is substantiated by observed changes in the recent past.

LITERATURE CITED

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. FAO, Rome

Alley WM (1984) The Palmer Drought Severity Index: limitations and assumptions. J Clim Appl Meteorol 23: 1100–1109

APCC (Austrian Panel on Climate Change) (2014) Österreichischer Sachstandsbericht Klimawandel 2014 (AAR14). Verlag der Österreichischen Akademie der Wissenschaften, Vienna

Auer I, Böhm R, Jurkovi A, Orlik A and others (2005) A new instrumental precipitation dataset for the greater Alpine region for the period 1800–2002. Int J Climatol 25: 139–166

Blaschke AP, Merz R, Parajka J, Salinas J, Blöschl G (2011) Auswirkungen des Klimawandels auf das Wasserdargebot von Grund- und Oberflächenwasser. Oesterr Wasser Abfallwirtsch 63:31–41

Bochníček O, Borsányi P, Čepčeková E, Faško P and others (2015) Klimatický atlas Slovenska (Climate Atlas of Slovakia). Slovenský hydrometeorologický ústav, Bratislava

Böhm R (2006) ALP-IMP (EVK-CT-2002-00148) Multi-centennial climate variability in the Alps based on instrumental data, model simulations and proxy data. Short version. (Final report for RTD-project). Central Institute for Meteorology and Geodynamics, Vienna

Brázdil R, Kirchner K (eds) (2007) Vybrané přírodní extrémy a jejich dopady na Moravě a ve Slezsku (Selected natural extremes and their impacts in Moravia and Silesia). Český hydrometeorologický ústav, Prague

Brázdil R, Chromá K, Dobrovolný P, Tolasz R (2009a) Climate fluctuations in the Czech Republic during the period 1961–2005. Int J Climatol 29:223–242

Brázdil R, Trnka M, Dobrovolný P, Chromá K, Hlavinka P, Žalud Z (2009b) Variability of droughts in the Czech Republic, 1881–2006. Theor Appl Climatol 97:297–315

Brázdil R, Zahradníček P, Pišoft P, Štěpánek P, Bělínová M, Dobrovolný P (2012) Temperature and precipitation fluctuations in the Czech lands during the period of instrumental measurements. Theor Appl Climatol 110:17–34

Brázdil R, Dobrovolný P, Trnka M, Kotyza O and others (2013) Droughts in the Czech Lands, 1090–2012 AD. Clim Past 9:1985–2002

Brázdil R, Trnka M, Mikšovský J, Řezníčková L, Dobrovolný P (2015a) Spring-summer droughts in the Czech Land in 1805–2012 and their forcings. Int J Climatol 35: 1405–1421

Brázdil R, Trnka M, Řezníčková L, Balek J and others (2015b) Sucho v českých zemích: minulost, současnost, budoucnost (Drought in the Czech Lands: past, present and future). Centrum výzkumu globální změny Akademie věd české republiky, Brno

Brázdil R, Dobrovolný P, Trnka M, Büntgen U, Řezníčková L, Kotyza O, Valášek H (2016a) Documentary and instrumental-based drought indices for the Czech Lands back to AD 1501. Clim Res 70:103–117

Brázdil R, Raška P, Trnka M, Zahradníček P and others (2016b) The Central European drought of 1947: causes and consequences, with particular reference to the Czech Lands. Clim Res 70:161–178

Büntgen U, Brázdil R, Dobrovolný P, Trnka M, Kyncl T (2011a) Five centuries of southern Moravian drought variations revealed from living and historic tree rings. Theor Appl Climatol 105:167–180

Büntgen U, Tegel W, Nicolussi K, McCormick M and others (2011b) 2500 years of European climate variability and human susceptibility. Science 331:578–582

Calanca P (2007) Climate change and drought occurrence in the Alpine region: How severe are becoming the extremes? Global Planet Change 57:151–160

Casty C, Wanner H, Luterbacher J, Esper J, Böhm R (2005) Temperature and precipitation in the European Alps since 1500. Int J Climatol 25:1855–1880

Chládová Z, Kalvová J, Raidl A (2007) The observed changes of selected climate characteristics in the period 1961–2000. Meteorol Čas 10:13–19

Christensen N, Wood A, Voisin N, Lettenmaier D, Palmer R (2004) Effects of climate change on the hydrology and water resources of the Colorado River basin. Clim Change 62:337–363

Cook ER, Seager R, Kushnir Y, Briffa KR and others (2015) Old World megadroughts and pluvials during the Common Era. Sci Adv 1:e1500561

Dai A (2013) Increasing drought under global warming in

observations and models. Nat Clim Change 3:52–58

Dai A, Trenberth KE, Taotao Q (2004) A global dataset of Palmer Drought Severity Index for 1870–2002: relationship with soil moisture and effects of surface warming. J Hydrometeorol 5:1117–1130

Degirmendžič J, Kozuchowski K, Zmudzka E (2004) Changes of air temperature and precipitation in Poland in the period 1951–2000 and their relationship to atmospheric circulation. Int J Climatol 24:291–310

Dobrovolný P, Rybníček M, Kolář T, Brázdil R, Trnka M, Büntgen U (2015) A tree-ring perspective on temporal changes in the frequency and intensity of hydroclimatic extremes in the territory of the Czech Republic since 761 AD. Clim Past 11:1453–1466

Dubrovský M, Svoboda MD, Trnka M, Hayes MJ, Wilhite DA, Zalud Z, Hlavinka P (2009) Application of relative drought indices in assessing climate change impacts on drought conditions in Czechia. Theor Appl Climatol 96: 155–171

Feng S, Trnka M, Hayes M, Zhang Y (2016) Why different drought indices show distinct future drought risk outcomes in the US Great Plains? J Clim (in press)

Fürst J, Nachtnebel HP, Kling H, Hörhan T (2008) Trends in Niederschlag und Abfluss. Mittblatt Hydrogr Dienst Oesterr 85:1–43

Hänsel S (2014) Introducing the decile concept for studying the spatiotemporal characteristics and variability of long-lasting dry and wet periods. Theor Appl Climatol 118: 223–235

Hanslian D, Brázdil R, Štekl J, Kakos V (2000) Vliv cyklon středomořského původu na vysoké denní úhrny srážek na Milešovce a Lysé hoře v období 1961–1995 (The effect of cyclones of Mediterranean origin on high daily precipitation totals at Mt. Milešovka and Mt. Lysá hora in the 1961–1995 period). Meteorol Zpr 53:33–41

Heim RR Jr (2002) A review of twentieth-century drought indices used in the United States. Bull Am Meteorol Soc 83:1149–1165

Hlavinka P, Trnka M, Semerádová D, Dubrovský M, Zalud Z, Mozný M (2009) Effect of drought on yield variability of key crops in Czech Republic. Agric Meteorol 149: 431–442

Horridge M, Madden J, Wittwer G (2005) The impact of the 2002–2003 drought on Australia. J Policy Model 27: 285–308

Kalis AJ, Merkt J, Wunderlich J (2003) Environmental changes during the Holocene climatic optimum in central Europe — human impact and natural causes. Quat Sci Rev 22:33–79

Kendall MG (1990) Rank correlation methods, 5th edn. Charles Griffin, London

Květoň V (2001) Normály teploty vzduchu na území české republiky v období 1961–1990 a vybrané teplotní charakteristiky období 1961–2000 (Climatological normals of air temperature of the Czech Republic in the 1961–1990 period and selected air temperature characteristics of the 1961–2000 period). Národní klimatický program České republiky, Prague

Kyselý J, Picek J, Huth R (2007) Formation of homogeneous regions for regional frequency analysis of extreme precipitation events in the Czech Republic. Stud Geophys Geod 51:327–344

Labudová L, Faško P, Ivaňáková G (2015a) Changing climate and changes in climate regions. Moravian Geogr Rep 23:71–82

Labudová L, Turňa M, Nejedlík P (2015b) Drought monitoring in Slovakia. In: Šiška B, Nejedlík P, Eliašová M (eds) Towards climatic services: proceedings of an international scientific conference, 15–18 September 2015, Nitra. Slovak University of Agriculture, Nitra

Lloyd-Hughes B, Saunders MA (2002) A drought climatology for Europe. Int J Climatol 22:1571–1592

Matulla C, Penlap EK, Haas P, Formayer H (2003) Comparative analysis of spatial and seasonal variability: Austrian precipitation during the 20th century. Int J Climatol 23: 1577–1588

McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time steps. In: Eighth conference on applied climatology, January 17–22, Anaheim, CA, p 179–184

Melo M, Lapin M, Damborská I (2007) Detection of climatic trends and variability at Hurbanovo. In: Střelcová K, Mátyás C, Kleidon A, Lapin M and others (eds) Bioclimatology and natural hazards. International Scientific Conference, 17 –20 September 2007, Pol'ana nad Detvou. Slovak Bioclimatological Society, Bratislava

Metzger MJ, Bunce RGH, Jongman RHG, Mücher CA, Watkins JW (2005) A climatic stratification of Europe. Glob Ecol Biogeogr 14:549–563

Palmer WC (1965) Meteorological drought. Office of Climatology Research Paper 45. US Weather Bureau, Washington, DC

Pecho J, Faško P, Melo M (2008) Precipitation deficit periods in the Danubian lowland in Slovakia. In: Brilly M, Šraj M (eds) 24th Conference of the Danubian Countries on the Hydrological Forecasting and Hydrological Bases of Water Management, 2–4 June 2008, Bled

Potop V, Boroneant C, Možný M, Štěpánek P, Skalák P (2014) Observed spatiotemporal characteristics of drought on various time scales over the Czech Republic. Theor Appl Climatol 115:563–581

Prescott JA (1940) Evaporation from a water surface in relation to solar radiation. Trans R Soc S Aust 64:114–118

Šercl P, Lett P (2002) Výpočet rastrůsrážek v prostředí GIS (s využitím ArcView Spatial Analyst). Uživatelská příručka verze 2.0.1. (Calculation of precipitation grid in the GIS using ArcView Spatial Analyst. User guide version 2.0.1). čHMÚ, OPV, Prague

Sheffield J, Wood EF, Roderick ML (2012) Little change in global drought over the past 60 years. Nature 491: 435–438

Škvarenina J, Tomlain J, Hrvol J, Škvareninová J, Nejedlík P (2009) Progress in dryness and wetness parameters in altitudinal vegetation stages of West Carpathians: time-series analysis 1951–2007. Idöjárás 113:47–54

Sönmez FK, Kömüscü AÜ, Erkan A, Turgu E (2005) An analysis of spatial and temporal variability dimension of drought vulnerability in Turkey using the Standardized Precipitation Index. Nat Hazards 35:243–264

Spinoni J, Naumann G, Carrao H, Barbosa P, Vogt JV (2014) World drought frequency, duration, and severity for 1951–2010. Int J Climatol 34:2792–2804

Spinoni J, Naumann G, Vogt J, Barbosa P (2015) European drought climatologies and trends based on a multi-indicator approach. Global Planet Change 127:50–57

Štěpánek P, Zahradníček P, Skalák P (2009) Data quality control and homogenization of air temperature and precipitation series in the area of the Czech Republic in the period 1961–2007. Adv Sci Res 3:23–26

Štěpánek P, Zahradníček P, Brázdil R, Tolasz R (2011)

Metodologie kontroly a homogenizace časových řad v klimatologii (Methodology of data quality control and homogenization of time series in climatology). Český hydrometeorologický ústav, Prague

Thaler S, Eitzinger J, Trnka M, Dubrovsky M (2012) Impacts of climate change and alternative adaptation options on winter wheat yield and water productivity in a dry climate in Central Europe. J Agric Sci 150:537–555

➤ Thornthwaite CW (1948) An approach towards a rational classification of climate. Geogr Rev 38:55–94

Tolasz R, Míková T, Valeriánová A, Voženílek V (eds) (2007) Atlas podnebí česka (Climate Atlas of Czechia). Český hydrometeorologický ústav, Prague

➤ Trenberth KE, Dai A, van der Schrier G, Jones PD, Barichivich J, Briffa KR, Sheffield J (2014) Global warming and changes in drought. Nat Clim Change 4:17–22

➤ Trnka M, Žalud Z, Eitzinger J, Dubrovský M (2005) Global solar radiation in Central European lowlands estimated by various empirical formulae. Agric Meteorol 131:54–76

➤ Trnka M, Dubrovský M, Svoboda M, Semerádová D, Hayes M, Žalud Z, Wilhite D (2009) Developing a regional drought climatology for the Czech Republic. Int J Climatol 29:863–883

➤ Trnka M, Kocmánková E, Balek J, Eitzinger J and others (2010) Simple snow cover model for agrometeorological applications. Agric Meteorol 150:1115–1127

➤ Trnka M, Kersebaum KC, Eitzinger J, Hayes M and others (2013) Consequences of climate change for the soil climate in Central Europe and the central plains of the United States. Clim Change 120:405–418

➤ Trnka M, Brázdil R, Možný M, Štěpánek P and others (2015) Soil moisture trends in the Czech Republic between 1961 and 2012. Int J Climatol 35:3733–3747

➤ van der Schrier G, Briffa KR, Jones PD, Osborn TJ (2006) Summer moisture variability across Europe. J Clim 19: 2818–2834

➤ van der Schrier G, Efthymiadis D, Briffa KR, Jones PD (2007) European alpine moisture variability 1800–2003. Int J Climatol 27:415–427

➤ van der Schrier G, Barichivich J, Briffa KR, Jones PD (2013) A scPDSI-based global dataset of dry and wet spells for 1901–2009. J Geophys Res 118:4025–4048

➤ van Loon AF, Ploum SW, Parajka J, Fleig AK, Garnier E, Laaha G, van Lanen HAJ (2015) Hydrological drought types in cold climates: quantitative analysis of causing factors and qualitative survey of impacts. Hydrol Earth Syst Sci 19:1993–2016

➤ Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multi-scalar drought index sensitive to global warming: the Standardized Precipitation Evapotranspiration Index. J Clim 23:1696–1718

➤ Viney NR, Bates BC (2004) It never rains on Sunday: the prevalence and implications of untagged multi-day rainfall accumulations in the Australian high quality data set. Int J Climatol 24:1171–1192

Wardlow BD, Anderson MC, Verdin JP (2012) Remote sensing of drought: innovative monitoring approaches. CRC Press, Boca Raton, FL

➤ Wells N, Goddard S, Hayes M (2004) A self-calibrating Palmer Drought Severity Index. J Clim 17:2335–2351

➤ White W, Mickeon G, Syktus J (2003) Australian drought: the interference of multi-spectral global standing modes and travelling waves. Int J Climatol 23:631–662

Wilhite DA (ed) (2000) Drought: a global assessment. Routledge Publishers, London

Wilhite DA (2005) Drought and water crises: science, technology, and management issues. CRC Press, Boca Raton, FL

Zahradníček P, Trnka M, Brázdil R, Možný M and others (2015) The extreme drought episode of August 2011– May 2012 in the Czech Republic. Int J Climatol 35: 3335–3352