Drought trends over part of Central Europe between 1961 and 2014

Miroslav Trnka¹,²,*, Jan Balek¹,², Petr Štěpánek¹,³, Pavel Zahradníček¹,³, Martin Možny²,⁴, Josef Eitzinger⁵, Zdeněk Žalud¹,², Herbert Formayer⁵, Maroš Turňa⁶, Pavol Nejedlík⁷, Daniela Semerádová¹, Petr Hlavinka¹,², Rudolf Brázdil¹,⁸

¹Global Change Research Institute, Czech Academy of Sciences, Bělidla 986/4a, 603 00 Brno, Czech Republic
²Department of Agrosystems and Bioclimatology, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic
³Czech Hydrometeorological Institute, Brno Regional Office, Kroftova 2578/43, 616 67 Brno, Czech Republic
⁴Czech Hydrometeorological Institute, Doksany Observatory, Doksany 105, 411 85 Doksany, Czech Republic
⁵University of Natural Resources and Life Sciences, Institute of Meteorology, Peter-Jordan Strasse 82, 1190 Vienna, Austria
⁶Slovak Hydrometeorological Institute, Jeseníka 17, 833 15 Bratislava, Slovakia
⁷Earth Science Institute, Slovak Academy of Science, Dúbravská cesta 9, 845 28 Bratislava, Slovakia
⁸Institute 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
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, Brázdíl 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 (Brázdíl et al. 2016b this Special) with less pronounced episodes since then in 1953–1954, 1959, 1992, 2000, 2003, 2007 (Brázdíl et al. 2015b) and most recently in 2011–2012 (Zahradiček 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, Brázdíl 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
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 measurements 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>
<thead>
<tr>
<th>SPI</th>
<th>SPEI</th>
<th>Z-index</th>
<th>PDSI</th>
<th>Drought index category</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥2.00</td>
<td>≥2.00</td>
<td>≥3.50</td>
<td>≥4.00</td>
<td>Extremely moist</td>
</tr>
<tr>
<td>1.50 to 1.99</td>
<td>1.50 to 1.99</td>
<td>2.5 to 3.49</td>
<td>3.00 to 3.99</td>
<td>Very moist</td>
</tr>
<tr>
<td>1.00 to 1.49</td>
<td>1.00 to 1.49</td>
<td>1.00 to 2.49</td>
<td>2.00 to 2.99</td>
<td>Moderately moist</td>
</tr>
<tr>
<td>−0.99 to 0.99</td>
<td>−0.99 to 0.99</td>
<td>−1.24 to 0.99</td>
<td>−1.99 to 1.99</td>
<td>Normal range</td>
</tr>
<tr>
<td>−1.00 to −1.49</td>
<td>−1.00 to −1.49</td>
<td>−1.25 to −1.99</td>
<td>−2.00 to −2.99</td>
<td>Moderately dry</td>
</tr>
<tr>
<td>−1.50 to −1.99</td>
<td>−1.50 to −1.99</td>
<td>−2.00 to −2.74</td>
<td>−3.00 to −3.99</td>
<td>Severely dry</td>
</tr>
<tr>
<td>≤−2.00</td>
<td>≤−2.00</td>
<td>≤−2.75</td>
<td>≤−4.00</td>
<td>Extremely dry</td>
</tr>
</tbody>
</table>
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 Republic

<table>
<thead>
<tr>
<th>Stages of drought episodes</th>
<th>SPI</th>
<th>SPEI</th>
<th>Z-index</th>
<th>PDSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>Drops below −1.0</td>
<td>Drops below −1.0</td>
<td>Drops below −1.25</td>
<td>Drops below −2.0</td>
</tr>
<tr>
<td>Minimum value</td>
<td>At least 1 mo below −1.5</td>
<td>At least 1 mo below −1.5</td>
<td>At least 1 mo below −2.0</td>
<td>At least 1 mo below −3.0</td>
</tr>
<tr>
<td>End</td>
<td>Rises above 0.0</td>
<td>Rises above 0.0</td>
<td>Rises above 0.0</td>
<td>Rises above 0.0</td>
</tr>
</tbody>
</table>
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](image-url)
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, 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

<table>
<thead>
<tr>
<th>Elevation (m a.s.l.)</th>
<th>No. of stations</th>
<th>Mean elevation (m)</th>
<th>1 mo scSPI</th>
<th>1 mo scSPEI</th>
<th>3 mo scZ-index</th>
<th>3 mo scSPI</th>
<th>3 mo scSPEI</th>
<th>12 mo scSPI</th>
<th>12 mo scSPEI</th>
<th>12 mo scPDSI</th>
<th>12 mo scPDSI index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer half year</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90–200</td>
<td>47</td>
<td>148</td>
<td>9 /45</td>
<td>13/6</td>
<td>13/6</td>
<td>6/36</td>
<td>36/0</td>
<td>0/6</td>
<td>26/0</td>
<td>38/0</td>
<td></td>
</tr>
<tr>
<td>200–400</td>
<td>157</td>
<td>296</td>
<td>18/34</td>
<td>34/8</td>
<td>39/7</td>
<td>18/29</td>
<td>51/4</td>
<td>2/15</td>
<td>22/1</td>
<td>48/3</td>
<td></td>
</tr>
<tr>
<td>400–600</td>
<td>124</td>
<td>495</td>
<td>26/40</td>
<td>44/6</td>
<td>44/5</td>
<td>14/44</td>
<td>51/6</td>
<td>2/31</td>
<td>10/3</td>
<td>31/6</td>
<td></td>
</tr>
<tr>
<td>600–1000</td>
<td>65</td>
<td>757</td>
<td>25/34</td>
<td>37/15</td>
<td>38/11</td>
<td>22/34</td>
<td>42/8</td>
<td>2/35</td>
<td>8/11</td>
<td>17/15</td>
<td></td>
</tr>
<tr>
<td>&gt;1000</td>
<td>18</td>
<td>1319</td>
<td>0/44</td>
<td>11/28</td>
<td>17/28</td>
<td>6/67</td>
<td>11/61</td>
<td>0/56</td>
<td>0/44</td>
<td>6/44</td>
<td></td>
</tr>
<tr>
<td>Environmental zone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAN</td>
<td>37</td>
<td>129</td>
<td>0/49</td>
<td>3/5</td>
<td>11/5</td>
<td>3/51</td>
<td>4/10</td>
<td>0/3</td>
<td>35/0</td>
<td>41/0</td>
<td></td>
</tr>
<tr>
<td>CON</td>
<td>312</td>
<td>440</td>
<td>18/35</td>
<td>35/8</td>
<td>37/7</td>
<td>15/34</td>
<td>46/6</td>
<td>2/24</td>
<td>16/3</td>
<td>38/6</td>
<td></td>
</tr>
<tr>
<td>ALS</td>
<td>59</td>
<td>662</td>
<td>42/46</td>
<td>51/15</td>
<td>51/14</td>
<td>25/41</td>
<td>53/15</td>
<td>0/34</td>
<td>0/15</td>
<td>20/14</td>
<td></td>
</tr>
<tr>
<td>All stations</td>
<td>411</td>
<td>457</td>
<td>20/37</td>
<td>34/9</td>
<td>36/8</td>
<td>16/37</td>
<td>46/7</td>
<td>1/24</td>
<td>15/5</td>
<td>35/7</td>
<td></td>
</tr>
<tr>
<td>Winter half year</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90–200</td>
<td>47</td>
<td>148</td>
<td>6/32</td>
<td>19/19</td>
<td>13/6</td>
<td>2/11</td>
<td>2/4</td>
<td>0/11</td>
<td>23/0</td>
<td>26/0</td>
<td></td>
</tr>
<tr>
<td>200–400</td>
<td>157</td>
<td>296</td>
<td>11/39</td>
<td>18/30</td>
<td>20/17</td>
<td>3/17</td>
<td>6/6</td>
<td>2/13</td>
<td>21/2</td>
<td>38/4</td>
<td></td>
</tr>
<tr>
<td>400–600</td>
<td>124</td>
<td>495</td>
<td>2/39</td>
<td>5/24</td>
<td>6/19</td>
<td>2/31</td>
<td>2/8</td>
<td>2/29</td>
<td>8/3</td>
<td>22/10</td>
<td></td>
</tr>
<tr>
<td>&gt;1000</td>
<td>18</td>
<td>1319</td>
<td>0/83</td>
<td>6/67</td>
<td>11/67</td>
<td>0/83</td>
<td>0/78</td>
<td>0/56</td>
<td>0/44</td>
<td>6/50</td>
<td></td>
</tr>
<tr>
<td>Environmental zone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAN</td>
<td>37</td>
<td>179</td>
<td>8/27</td>
<td>24/16</td>
<td>16/0</td>
<td>8/0</td>
<td>8/0</td>
<td>0/5</td>
<td>30/0</td>
<td>35/0</td>
<td></td>
</tr>
<tr>
<td>CON</td>
<td>312</td>
<td>440</td>
<td>6/43</td>
<td>12/30</td>
<td>14/21</td>
<td>2/28</td>
<td>4/11</td>
<td>2/22</td>
<td>15/3</td>
<td>29/9</td>
<td></td>
</tr>
<tr>
<td>ALS</td>
<td>59</td>
<td>662</td>
<td>2/42</td>
<td>2/44</td>
<td>2/47</td>
<td>0/47</td>
<td>0/37</td>
<td>0/31</td>
<td>0/15</td>
<td>10/25</td>
<td></td>
</tr>
<tr>
<td>All stations</td>
<td>411</td>
<td>457</td>
<td>6/42</td>
<td>11/31</td>
<td>12/23</td>
<td>2/29</td>
<td>4/15</td>
<td>1/22</td>
<td>14/5</td>
<td>26/11</td>
<td></td>
</tr>
</tbody>
</table>


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 hot-spots; 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 ($\alpha = 0.05$, 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.
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
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 incorpor-
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). Spínoni 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 CO₂ 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 Květš (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 (Degirmendžić 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.

Acknowledgements. M.T., R.B., P.H., J.B., D.S., P.Z., Z.Ž. and P.S. acknowledge funding from the Ministry of Education, Youth and Sports of the Czech Republic within the National Sustainability Program I (NPU I), grant number LO1415. R.B. also acknowledges Grant Agency of the Czech Republic for project no. 13-19831S. The work of J.E. and M.T. was supported by the Specific University Research Sustainability Program I (NPU I), grant number LO1415. R.B. also acknowledges Grant Agency of the Czech Republic for Youth and Sports of the Czech Republic within the National Sustainability Program I (NPU I), grant number LO1415. R.B.

LITERATURE CITED


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


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


Dai A (2013) Increasing drought under global warming in
observations and models. Nat Clim Change 3:52–58


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


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


Editorial responsibility: Donald Wilhite (Guest Editor), Lincoln, Nebrasca, USA

Submitted: March 29, 2016; Accepted: August 4, 2016

Proofs received from author(s): September 7, 2016