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Developing a Regional Drought Climatology for the Czech Republic

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Abstract

This study presents a methodology for the analysis of a drought climatology within a particular region that enables a user to define drought areas at a high spatial resolution. It is suitable for quantifying the relative differences in the intensity of drought spells, and the frequency and duration between individual stations within an area of interest. The methodology is based on the Standardized Precipitation Index (SPI), the Palmer Drought Severity Index (PDSI), and the Palmer Z-index (Z-index). However, the climatological parameters needed to process and calculate the indices were not derived separately for each site as is usually done but were based on a set of all available weather stations in the studied region. This approach was utilized in the case study including all of the Czech Republic using 233 climatological stations with monthly records of mean temperature and precipitation for the period 1961–2000. The study is also focused on the development of more efficient ways of communicating results to the stakeholders. Therefore, a method allowing for an integration of several drought indices into a single indicator called the Integrated Climatological Drought Indicator (ICDI) was developed. The newly developed method allowed for an objective identification of the drought-prone regions of the country that were defined as areas with a chance (higher than 50 and 60% respectively) of moderate or extreme drought. We have found that 12.3 and 3% of the country area, respectively, belong within these categories and that these regions also happen to be prime agricultural areas. The conclusions were supported by the results of a cluster analysis. Finally, the analysis of time trends was conducted, which showed that the majority of 233 stations had grown significantly drier during the studied period. The main driving force behind this development was found to be an increase of temperature, especially in the 1990s.

Keywords: drought climatology, scPDSI, scZ-index, scSPI, rPDSI, rZ-index, rSPI, cluster analysis

1. Introduction

The drought phenomenon is referred to as the most complex and least understood of all natural hazards, affecting more people than have been affected by any other extreme event (Wilhite, 2000). Drought should be perceived as a natural aspect of climate under all climatic regimes, as it occurs in both humid and arid areas (clearly with different impacts unique to the existing ecosystems). Central Europe is not frequently thought of as being a particularly drought-prone region in the European context with the exception being the Panonian Basin that, in part, includes eastern Austria and a large part of Hungary. As a consequence, only recently has the importance of a systematic research of drought climatology been recognized in countries like the Czech Republic, where high dependency on precipitation as the main source of water might lead to future conflicts between competing water users. Incorrect estimation of drought risk or omitting drought-related issues in the process of strategic planning might have serious consequences not only for the stability of the remaining natural ecosystems, but also for the economy and society as a whole. This is partly due to the fact that there is a marked distinction between impacts of short-term extreme events (e.g., floods or severe storms) and persistent ones (e.g., drought). Unlike drought, short-term extreme events tend to be neutral, or even stimulating, for economic growth in developed countries through higher public and private spending on the reconstruction efforts that follow. On the other hand, a prolonged drought spell might not only inflict severe economic losses but can potentially paralyze agricultural production over several seasons and restrain other segments of the economy as well (e.g., White et al., 2003 or Horridge et al., 2005).

The high vulnerability and devastating effects of droughts that are commonly associated with specific climatic regions (e.g., African Sahel, or recently in Australia) are rarely experienced in Central Europe. However, even here drought episodes have played an important role since the early Neolith, when relatively short drought periods significantly influenced the location of early settlements (Kalis et al., 2003). Recently, the region was faced with the so-called "green droughts," i.e., droughts associated with still relatively ample annual rainfall amounts (especially compared to the arid regions) but reduced agricultural productivity due to poorly timed rains. The most severe of these events was recorded in 1947 with less pronounced ones seen in 1978 and 1994 (Blinka, 2005 or Brázdil, 2007). A recent wave of drought episodes was experienced throughout Central Europe during 2000, 2001, and particularly 2003. The last event was the result of a prolonged period of suboptimal rainfall, combined with extremely high summer temperatures (e.g., van der Schrier et al., 2007). It influenced a full range of ecosystems throughout Central Europe, affecting some of the basic ecosystem services, starting with fodder production (Schaumberger et al., 2006) and ending with carbon sequestration (Ciais et al., 2005).

The mentioned example of risks associated with drought occurrence was the main motivation behind the present study of drought climatology. It takes advantage of the climatological dataset for 1961–2000 for 233 stations that were used in the Atlas of the Climate of Czechia (Tolasz et al., 2007). The main objectives of this study can be defined as follows: (1) to develop and test methods of drought assessment that will allow for a spatial description of drought climatology, (2) to apply these methods in evaluating drought risk in the Czech Republic, (3) to identify homogeneous regions according to their drought characteristics using a cluster analysis, and (4) to evaluate possible trends in drought occurrence during the studied period.

2. Materials and methods

Any realistic definition of drought must be region and application specific. Four interrelated categories of drought are usually distinguished based on the timescale and impact: meteorological, agricultural, hydrological, and socioeconomic (e.g., Heim, 2002). Agricultural drought impacts are mostly associated with timescales from weeks up to 6–9 months, while hydrological and socioeconomic impacts usually become apparent following longer time lags. The individual drought categories and their timescales are obviously overlapping. 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 specific impacts of this phenomenon. For this purpose, the evaluation of drought indices is frequently used to examine meteorological drought as they are convenient and relatively simple. Three of the most frequently used drought indicators, i.e., the Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), and Palmer Z-index (Z-index), were utilized in this study.

2.1. Input data

Figure 1(a) and (b) shows the Czech Republic's main soil characteristics and orographic features, as well as the applied set of climatological stations. The stations are listed in Appendix A, table AI, which also includes their basic climatological characteristics. The database was the result of a concerted effort between the Czech Hydrometeorological Institute and the National Climatic Program, as a part of preparing the Climatic Atlas of Czechia. The 233 stations (1 per 335 km^2) were selected from a dataset of 782 stations based on the quality and completeness of observations. The data were homogenized and checked for consistency prior to use (Tolasz, 2002; Tolasz et al., 2007). The station elevations are spread between 157 and 1490 m above sea level, with the mean altitude of the stations being 435 m, which is close to the country mean altitude (430 m) provided by the Czech Statistical Office (CSO, 2005). The mean annual temperature and sum of precipitation are almost identical to the mean climatological values for the Czech Republic (CSO, 2005). The warmest month is usually July with January or February being the coldest. The summer season (June–August) is typically characterized as the wettest with precipitation amounts accounting for 37% of the annual totals (ranging from 27 to 43%) on average. On the contrary, winter is typically the driest season accounting for around 18% of the annual precipitation (from 11 to 28%) followed by fall and spring. The only exceptions to this general pattern are two sites (105 and 112—Appendix A, table AI) found in the northern mountainous region of the country, where winter precipitation is slightly higher than in summer.

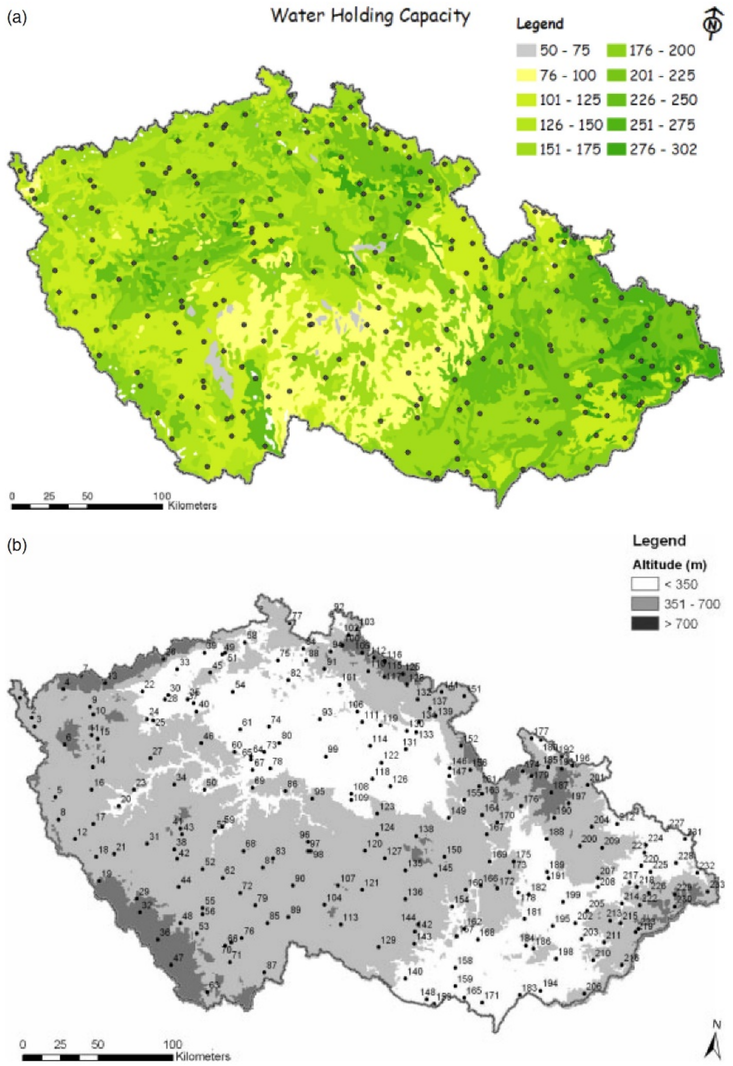


Figure 1. Soil water-holding capacities in the rooting zone within the study region: (a) location of 233 climatological stations in the Czech Republic used in the study; (b) the three classes of elevation in the latter map are designed to approximate the different forms of dominant land-use types in the region: (1) below 350 m mostly intensive agriculture;

(2) between 350 and 700 m less intensive agriculture (usually less favorable areas) and forests; and (3) above 700 m with limited agricultural production and mostly forested. The complete list of the stations, including the basic parameters, are found in Appendix A, table AI.

In this study, we deal with drought in timescales ranging from 1 to 12 months, although we are aware of the fact that shorter time steps would be needed to study certain aspects of drought impacts on agriculture. However, selecting a time step shorter than 1 month would reduce data availability for the study, and thus, it was decided to analyze drought on a monthly timescale. In fact a large number of researchers prefer monthly data for various reasons including better availability (e.g., Lloyd-Hughes and Saunders, 2002; Dai et al., 2004 or van der Schrier et al., 2007) and lower sensitivity to observational errors (e.g., Viney and Bates, 2004).

The climatological data were complemented with values of the maximum soil water-holding capacity (MSWC) for each 0.5 km× 0.5 km grid. This parameter was estimated using a combination of digitalized maps of soil types (1:500,000) and detailed soil physics data from 1,073 soil pits collected during the Czech National Soil Survey (fig. 1(a)). For each of the 25 soil types, a mean value of MSWC was determined to be an average of the maximum water-holding capacities of all soil pits of a particular soil type in the database. The MSWC of the individual soil types ranges from 50 to 302 mm and was determined by the weighted soil water-holding capacities of individual soil horizons up to the maximum rooting depth determined at each soil pit.

2.1.1. Standardized Precipitation Index

The assessment of meteorological drought is mostly based on rainfall. This can be done either by analyzing the rainfall amounts in terms of reliability (e.g., Laughlin et al., 2003) or by using one of the many precipitation-based drought indices that have been developed over time (e.g., McKee et al., 1993 or Byun and Wilhite, 1999). One of the most recent and widely accepted indicators is the SPI, which allows for drought evaluation at multiple timescales using either monthly or weekly precipitation data. Mathematically, the SPI is based on the cumulative probability of a given rainfall event occurring at the given station (McKee et al., 1993). The historic rainfall data of the station are usually fitted by using a gamma distribution, which has been found to fit the precipitation distribution of most timescales quite well. Gamma distribution suitability for the area of Central Europe has been recently confirmed in the pan-European study comparing several distribution functions (Lloyd-Hughes and Saunders, 2002). The fitted cumulative probability function is then transformed by an inverse normal function. A low or high probability on the cumulative probability function related to a particular rainfall amount then indicates a likely dry or wet event, respectively. In summary, the SPI can effectively represent the amount of rainfall over a given timescale in relation to the median. This enables the user to state whether or not a station is experiencing dryness as the landscape (as well as management practices in it) are considered to be adjusted to the regional climate optimum. This near-optimum range of SPI could be approximated by the interval of ±0.9, while the usual range of SPI values ranges from −3 to +3, with negative values describing periods of precipitation below the median. McKee et al. (1993) defined the criteria for a "drought event" and used the SPI to classify various drought intensities (table I). In this study, we define the start of a drought episode as a period during which the SPI value remains negative and falls below −1.0 at least once during the episode.

Table I. Standardized Precipitation Index (SPI), Palmer Z-index (Z-index), and Palmer Drought Severity Index (PDSI) categories according to Heim (2002)

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

The SPI enables the user to assess the occurrence of short-term (duration of the order of 1 month), medium-term (from 3 to 12 months), and long-term droughts (12 months and longer). When we analyze regions with different precipitation amounts at individual stations, but with similar annual patterns of rainfall distribution, the SPI results will inevitably indicate the same number of dry episodes regardless of the precipitation totals. While this SPI feature is of particular value when it is used for drought monitoring, it hampers its use as a tool for regional classification of a drought climatology. This intrinsic property of the SPI could be partially bypassed through evaluating those SPI parameters that preserve their variability in space (e.g., Lloyd-Hughes and Saunders, 2002 or Sönmez et al., 2005). But 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 is not very suitable for communication with the stakeholders. Therefore, we propose a modification of the SPI calculation that is, in our view, better suited for spatial drought climatology studies. From now on we refer to this method as the "relative Standardized Precipitation Index" (rSPI), while the original version of SPI is marked as scSPI. In the rSPI, the parameters of the gamma distribution are based on the set of data created by aggregating all monthly precipitation totals from the 233 stations during the 1961–2000 period. In the following steps, the values of the rSPI relative to the reference distribution function were derived for each site. This enabled us to compare the precipitation deviation for each station and each month by utilizing the distribution function that represented the climate optimum of the given region rather than that of the individual station. The method complements the recent work of other authors (e.g., Rossi et al., 1992; Lloyd-Hughes and Saunders, 2002 or Hisdal and Tallaksen, 2003) who emphasize the regional nature of drought and the necessity of studying it within a regional context. Figure 2(a) and (b) illustrates the differences between the scSPI and rSPI 12-month values at two sites (Žatec—a lowland semiarid station and the mountainous Lysá Hora station) from January 1961 to December 2000. It is clear that the time series of the rSPI preserve the same temporal behavior as the original scSPI, which can be documented by Pearson correlation coefficient values ranging between 0.96 and 1.00. While the values of rSPI (Figure 2(b)) for Žatec indicate a climate which is significantly drier than the regional climate, the wetness of the mountainous station of Lysá Hora is depicted well by the corresponding rSPI values. Obviously, the interpretation of the rSPI outputs and relative indices, in general, always needs to be made within the context of the regional climate, and it does not automatically mean that upper elevated locations are immune from drought, especially when the relatively high dependency of some mountainous ecosystems on regular precipitation and generally very low soil water-holding capacity in these regions are taken into account. More on the use of relative indices could be found in Dubrovský et al. (2008).

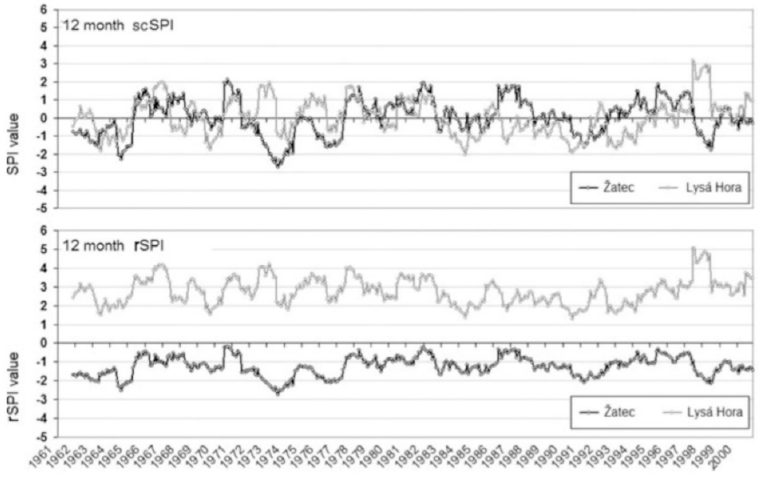


Figure 2. Comparison of 12-month scSPI (a) and 12-month rSPI (b) values for the 1961–2000 period. The station Žatec (273 m a.s.l.) is one of the driest sites in the Czech Republic with a mean annual precipitation of 444 mm, in contrast to Lysá Hora (1322 m a.s.l.), which is the wettest site in the dataset (with a mean annual precipitation of 1407 mm).

2.1.2. Palmer Drought Severity Index and Palmer Z-index

The PDSI (Palmer, 1965) is one of the most complex and widely used methods of quantifying drought throughout the world (e.g., Szinell et al., 1998; Lloyd-Hughes and Saunders, 2002; Ntale and Gan, 2003; Dai et al., 2004 or van der Schrier et al., 2006, 2007). A comprehensive overview of the necessary calculation procedures needed to derive PDSI is given by Palmer (1965); Alley (1984); Ntale and Gan (2003) and most recently by van der Schrier et al. (2006, 2007) and thus it is not necessary to furnish the entire calculation procedures.

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) method. It applies a two-layer bucket-type model for soil moisture computations with three assumptions relating to the soil profile characteristics: (1) the water-holding capacity of the surface layer (Ss) is set at a maximum of 25 mm; (2) the water-holding capacity of the underlying layer (Su) has a maximum value dependent on the soil type and (3) water transfer into or out of the lower layer only occurs when the surface layer is full or empty, respectively. The PDSI itself can be described as an accumulative departure relative to local mean conditions in atmospheric moisture supply and demand at the surface (Palmer, 1965) and it is thought to represent well the episodes of prolonged drought. The method of PDSI calculation includes an intermediate term known as the Palmer moisture anomaly index (or Z-index), which is a measure of surface moisture anomaly for a current month without consideration of the antecedent conditions that are so characteristic of the PDSI. It is basically the moisture departure, d, adjusted by a weighing factor called the climatic characteristic, which is denoted by K (Equation (1)).

$$Z = Kd \tag{1}$$

The Z-index can therefore be used to track agricultural droughts as it responds relatively quickly to the changes in soil moisture (Karl, 1986). Due to the Z-index's ability to rank the dryness or wetness of individual months, we decided to use it as one of the indicators of short-term drought spells. The Z-index is related to the PDSI through the following equation (Palmer, 1965):

$$PDSI_i = PDSI_{i-1} + \frac{Z\text{-}index_i}{3} - 0.103PDSI_{i-1} \tag{2}$$

where *i* stands for index value in the given month.

The original monthly PDSI relies on empirical constants, soil property assumptions, and climate characteristics derived by Palmer (1965) using data from nine stations in Kansas and Iowa (USA). In this study, the so-called self-calibrated version (Wells et al., 2004) of the Z-index and PDSI were used. Wells et al. (2004) modified the original Palmer model in order to adjust the former empirical constants automatically according to the input data uniquely derived from each studied location. The self-calibrated PDSI also adjusts the value of K in order to obtain a range of PDSI values between −4.0 and +4.0, thus partly mitigating regional differences between drought events of the same intensity.

Owing to the complexity of the index we noted the tendency of the PDSI to exhibit large sudden changes at some stations between individual months (Dubrovský et al., 2005) and similar behavior was reported by Ntale and Gan (2003). In the case of Czech stations, the fluctuation took place in the near-normal range and only on rare occasions crossed the dry/wet event thresholds. Therefore, they did not exert any significant influence on our drought climatology assessment results even though such erratic behavior could be problematic when the method is used in drought monitoring. Other frequently listed shortcomings of the PDSI were either directly addressed during our work (e.g., soil type specific water retention capacities were at our disposal) or were not considered to be important at the resolution and timescales of the study (e.g., assumption of no runoff unless soil moisture is at field capacity, lack of snow cover module or dependence of Thornthwaite PET method estimates based on latitude only). Parallel use of the SPI and Z-index also partially mitigated the time lag in the determination of drought onset (seen in the PDSI), which is known to be about 1 month (or more) when compared to the SPI (Hayes et al., 1999). The process of "self-calibration" of the PDSI (and Z-index as well) prevents interstation comparisons as the PDSI (or Z-index) assigns the same value to different absolute terms of water deficit/excess. In order to better describe the drought climatology of the region, we modified the calculation procedures of both Palmer indices and we refer to them as the relative Palmer Drought Severity Index (rPDSI) and relative Z-index (rZ-index). The empirical coefficients of both indices (namely, the K value) were based on 9,320 years of data considering that they originated from a single station (i.e., set of all monthly observed values from 233 stations covering the Czech Republic during the period 1961–2000). In the following step, the departure from normal moisture levels (d) was calculated for each station, and the resulting rZ-index value enabled us to distinguish differences between individual sites. In the last step, the rPDSI value was determined using the same procedure as that of the PDSI. This approach made it possible to compare each month's soil moisture anomaly to the distribution that served as a representation of the overall country climatic conditions. A drought episode according to the rZ-index and rPDSI was defined as a continuous period of index values less than -1.0 as long as the index hits -2.0 at least once during the episode.

2.1.3. An integrated climatological drought indicator

In order to communicate the study results better to the stakeholders and policy makers, we developed a new indicator and calculated the percentage of months during the 1961–2000 period that fell into a drought spell according to rSPI, rZ-index, and rPDSI. This Integrated Climatological Drought Indicator (ICDI) combined both the number of drought events and their duration and allowed us to visualize drought risk over the area by utilizing a single map. The major shortfall of this approach was that it did 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. The ICDI was based on the mean percentage of months in a drought spell calculated from results of the 1- and 3-month rSPI, rZ-index and rPDSI in order to accommodate short-, mid-, and long-term droughts. All four indicators used in the process were given the same weights. The ICDI takes into account not only precipitation-deficit-based indicators (i.e., the rSPI) but also includes the effect of temperature and soil properties (applying rZ-index or rPDSI) within a single, robust indicator of climatological drought risk. Its main purpose is to give a simple but objective measure of dryness of a given area using readily available and sufficiently dense input data.

2.1.4. Spatial analysis techniques

In constructing the maps, we took advantage of the dependence of climatological drought parameters on the northing, easting, and elevation, and in the case of the rPDSI and rZ-index, we also took into account the soil water-holding capacity of the given site. In the first step, the value of the particular drought parameter (e.g., number of drought events or mean drought duration) was calculated for all 233 stations in the Czech Republic (fig. 1). In the next step, a polynomial regression function (using not only squares but also the first order interactions of the independent variables) was fitted to the data. During an extensive testing of various interpolation methods, we found that the polynomial regression model performed with smaller bias compared to standard interpolation methods, such as kriging, co-kriging, or thin-plate spline. This technique is better at capturing the spatial variability of drought, which does depend strongly on elevation and soil conditions. It was assumed that the relationship between dependent and independent variables differs insignificantly throughout the country and only one function was used for each parameter. The assumption was tested when the set of 233 stations was divided into two parts (east and west) and the results of the analysis for both regions were compared with those for the whole territory. In addition, every regression function was reevaluated by comparing the interpolated results with the station-based data using 14 extra weather stations as an independent data sample. The overall fit of the polynomial regression function to the site data was assessed by looking at the relative root mean square error (RMSE) and Pearson's coefficient of correlation (fig. 3). The first parameter gives an indication of the mean deviation of the estimated values compared to the magnitude of the estimated parameter. The latter represents the strength of the correlation between the particular drought characteristics and geographical location in combination with the soil conditions. We found both indicator values to be in the range (fig. 3) allowing for the use of the mapping technique. In addition, the polynomial regression method does not suffer from "edge effects" when compared to most standard interpolation techniques. This is of considerable importance given the problematic access to climatic databases in neighboring countries and issues of transborder data homogeneity.

Data for site elevations entered our calculations in the form of a smoothed terrain model in order to suppress small-scale local effects. Results were presented using two resolutions: (1) 0.5 km× 0.5 km grid cells; and (2) 0.5 km× 0.5 km grid, cells aggregated to cadastre units. Cadastre units constitute the smallest administrative region in the Czech Republic, and most of the planning or subsidy distribution (e.g., determination of drought compensation) is carried out at this administrative level. While a 0.5 km× 0.5 km grid resolution is convenient for a relatively detailed climatological study, in some cases it is convenient to provide outputs for various administrative regions (like in the case of ICDI). Thus, it makes good sense to provide climatological outputs for the same unit in order to facilitate their use. In the final step, the maps were checked for internal consistency and compared with other methods of drought assessment (e.g., water deficit defined as difference between potential evapotranspiration and actual precipitation) provided by Tolasz et al. (2007).

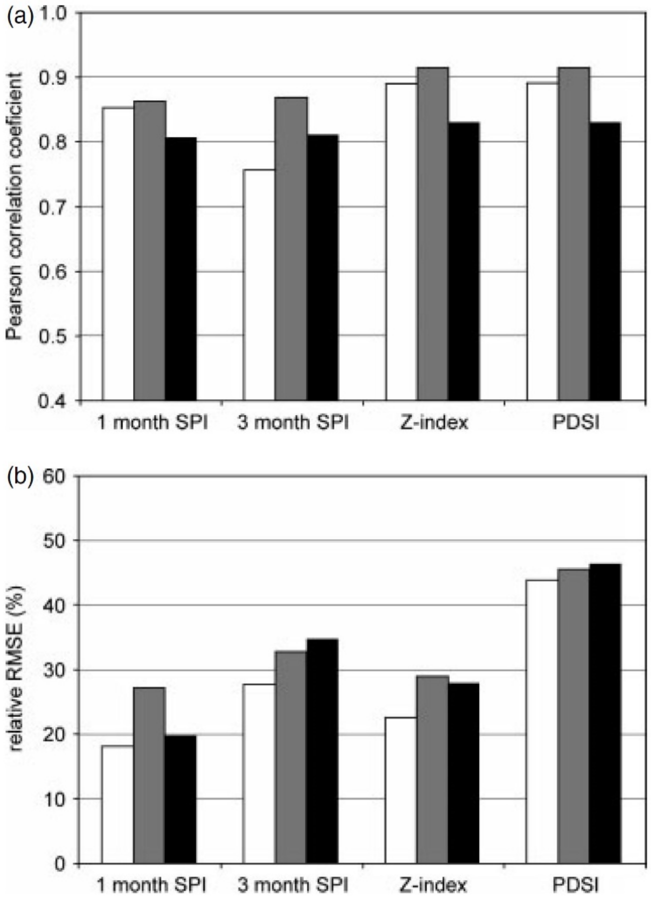


Figure 3. Results of the verification of the spatial analysis method. The charts indicate goodness-of-fit between values estimated using a polynomial regression function (PRF) for selected drought characteristics: White bar—number of drought events; gray bar—proportion of months in drought episode during (April–September); and black bar—mean duration of drought episodes. The goodness-of-fit is described in terms of a Pearson correlation coefficient and root mean square error (RMSE). The set of an additional 14 evenly distributed climatological stations that were not used for development of the PRF was utilized in this evaluation.

2.1.5. Cluster analysis

One of the aims of this study was to identify groups of sites with similar drought characteristics in order to verify results of previous spatial analyses. We found cluster analysis to be a suitable tool to spot similar regions as it allows for usage of multiple criteria in the process of station grouping. It has also been frequently used in order to determine similar groupings of stations to optimize networks of weather stations (DeGaetano, 2001), determine climatologically homogeneous regions (e.g., Matulla et al., 2003 or Unal et al., 2003) and also for grouping stations according to the occurrence of particular extreme events (e.g., Kyselý et al., 2007). One of the key advantages over other commonly used statistical methods is that cluster analysis is not based on a priori assumption of data distribution. However, it necessitates careful selection of the used cluster method and dissimilarity metrics. The number of drought episodes and their mean duration based according to the 1- and 3-month rSPI, rZ-index, and rPDSI were used as clustering parameters. Out of the five commonly used hierarchical clustering methods (i.e., single linkage, complete linkage, centroid, Ward's minimum variance and the average distance) we focused particularly on the performance of the complete linkage and Ward's minimum variance methods, as neither of them is known to be prone to the chaining (snowball) effect (Kalkstein et al., 1987). Since the stability of the clusters was one of the most important indicators, we compared the performance of various clustering methods over a subset of 190 stations and compared them with the results derived from using the complete database of 233 sites. The procedure followed suggestions made by Unal et al. (2003) and uncovered a higher stability using Ward's minimum variance method over the average linkage approach. In the case of the former method, the majority of the stations were found to be clustered into the same group in both runs. Interestingly, within the Czech Republic, Ward's method was found to produce the best results in a regional analysis of extreme precipitation events (Kyselý et al., 2007), which included the number of dry days as one of the input variables.

2.1.6. Trend analysis

Besides the frequency and duration of drought during the given time period (i.e., 1961–2000) the eventual trends in frequency and/or severity of the drought events during the study period constitutes important information for further analyses. Timescales of 1-, 3-, 6-, and 12-month SPI, PDSI, and Z-index monthly time series from 1961–2000 were tested by regression analysis using a 5% significance level as a threshold for the trend's statistical significance. In the case of the trend analysis, the original methods of index calculations (rather than their relative versions) were used. In order to avoid any existing autocorrelation between consecutive drought index values, the trends were evaluated separately for each month. Under these circumstances, all values in each of the 12 series can be considered independent. For every station we evaluated the number of months with statistically significant trends toward drier/wetter conditions. At sites where no statistically significant trends were recorded we counted the number of months having the same tendency of the regression line as an indication of drought development.

3. Results

3.1. Dry spells during 1961–2000

As Szinell et al. (1998) pointed out when considering the drought severity on a country-wide scale, both the intensity and spatial extent are important. Due to the relatively large number of stations and good spatial coverage (fig. 1), we chose the percentage of stations in severe or extreme drought (table I) to be an indicator of the drought's spatial extent. As seen in figure 4(a), the number and spatial extent of short-term drought events as recorded by the 1-month SPI is significantly higher than those of longer drought spells (figure 4(b)–(d)). We found that according to the 1-month SPI, more than 80% of the stations were affected by a severe or extreme drought spell during four independent episodes. Out of these, the drought episode of December 1972 was quite unique as all but four stations were hit by severe or extreme drought, and the only reason it went largely unnoticed was due to its timing (falling outside of the growing season). During the main vegetation season (i.e., from April to September) there were four short-term drought spells (impacting agricultural production) affecting more than 60% of the stations. In some cases (i.e., 1972) a single short-term event was a precursor to a long-term drought episode, which then led to serious hydrological impacts (e.g., low reservoir levels, limited stream flows, and depletion of groundwater). The most pronounced of these long-term droughts actually started at some locations earlier in summer 1971 and peaked during August–October 1973. During 1961–2000 there were four other long-term drought episodes that affected more than 40% of the stations during a single month. One should also bear in mind that impacts of drought tend to materialize after a certain delay, or lag. While agricultural droughts see a more rapid onset of impacts within a few weeks' time at most, at least in the case of rain-fed agriculture systems of Central Europe (e.g., Trnka et al., 2005), the hydrological parameters are known to be affected by drought after a delay of 2–3 months (Stefan et al., 2004).

While the results obtained using the Z-index are rather similar to those of the 1-month SPI, the percentage of stations in drought according to PDSI values best correlates with the 12-month SPI. As figure 4(f) shows, there were four major drought spells during 1961–2000 with the worst one occurring between 1990–1995. Despite a slightly lower intensity of this drought episode (when compared to the years 1974 and 1984), the uniqueness of this event is marked by its duration. During this drought spell, one-fifth of the stations were affected for 39 consecutive months, and as Brázdil (2007) reported for some southeastern stations, it was the longest single drought episode in the past 150 years.

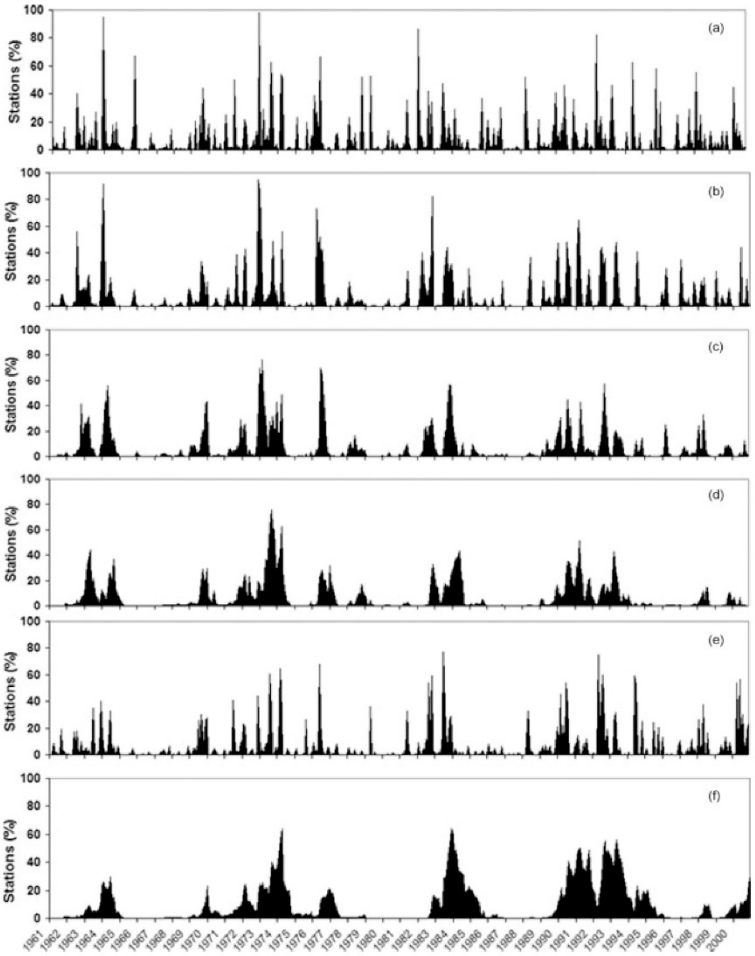


Figure 4. Proportion of the stations in a given month recording a moderate to extreme drought spell during 1961–2000 according to different drought indicators: (a) 1-month scSPI; (b) 3-month scSPI; (c) 6-month scSPI; (d) 12-month scSPI; (e) scZ-index, and (f) scPDSI).

3.2. Definition of drought-prone regions

Application of the rSPI, rZ-index, and rPDSI allowed for the spatial characterization of drought frequency and duration. As can be seen in figure 5(a), the highest number of drought events (according to the 1-month rSPI) occurs in the north, central, and southeastern regions of the country. Dry episodes in these areas are distinguished by their substantially higher intensity and longer duration, exceeding 4 months on average. On the contrary, dry episodes are rarely observed in the mountainous regions along the north, northwestern, east, and southwestern borders of the country. Nevertheless, occurrence of short-term drought spells cannot be completely ruled out even at these locations, which are generally characterized by elevations over 800 m with a mean annual precipitation sum greater than 800 mm. When they do occur, these episodes tend to be short with rSPI values rarely reaching below −2.0. Interestingly, there are also lowland sites having a negligible probability of drought occurrence in the northeast around the area of Moravian Gate (fig. 1(a)). The decisive factor contributing to the lower drought risk in this area is in its enhanced precipitation, which is 60% higher on average when compared to the corresponding lowland areas found in the southeastern region of the country (Tolasz et al., 2007). This can be explained by the distinctly different precipitation regimes due to a higher frequency of slowly moving Mediterranean cyclones in the northeastern part of the Czech Republic (Kyselý et al., 2007).

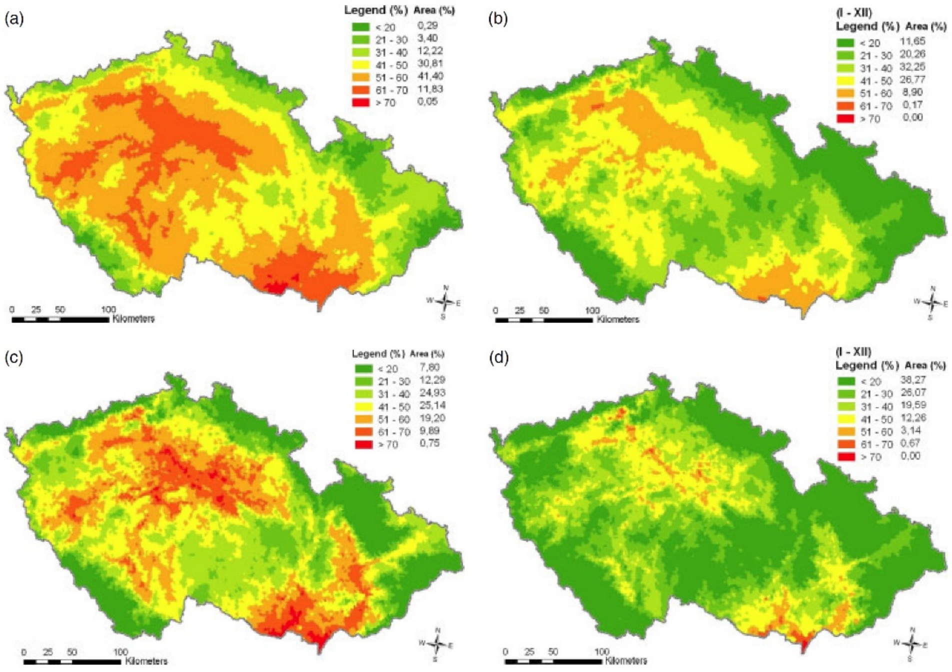


Figure 5. Number of drought spells according to the 1-month rSPI (a) and rZ-index respectively (c); proportion of months within drought episodes according to 1-month rSPI (b) and rZ-index (d) during the period 1961–2000. The drought characteristic on maps (a) and (c) are calculated using a 0.5 km× 0.5 km grid. The proportion of months within a drought episode (b, d) was integrated on the cadastre unit level.

While assessing the drought climatology of the Czech Republic we took advantage of rSPI's ability to be applied to arbitrarily long periods of aggregation. Therefore, we also analyzed 3- and 12-month rSPI values in order to evaluate mid- and long-term drought episodes. Although the absolute number of dry episodes decreases with increasing aggregation, these episodes tend to be much longer and show a much higher level of persistence as McKee et al. (1993) noted when analyzing the Boulder (CO) series. Despite the lower absolute number of individual episodes of medium and long-term droughts (represented by the 3- and 12-month rSPI), the percentage of months affected by these droughts is markedly higher than that in the case of short-term droughts (those represented by the 1-month rSPI index). For example, the percentage of months affected by drought according to the 3-month rSPI can be up to 70% in Southern Moravia, Central Bohemia, and the Elbe river basin, while episodes of short-term droughts account for only 50% of the months in the same areas. Applying the 3- and especially the 12-month rSPI indices also resulted in enhancing the differences between lowland areas and the mountains, where several consecutive months with a high precipitation deficit are highly unlikely. Comparison of figure 5(a) and (c) shows that inclusion of the temperature and soil water-holding capacity in the drought evaluation process results in a much higher spatial heterogeneity within the drought climatology of the individual regions. Both the 1-month rSPI (fig. 5(a) and (b)) and the rZ-index (fig. 5(c) and (d)) indicate that the highest probabilities of drought events are found to occur in the north, central, and southeastern regions of the country. However, at the local level drought risk is clearly differentiated according to the soil properties. Figure 5(d) indicates that the highest drought risk is found on the alluvial soils within Morava and the Elbe river basins. In addition, two smaller drought "epicenters" can be found in the lowlands of southern and southwestern Bohemia. Their drought susceptibility is due to the relatively low precipitation and high potential of evapotranspiration found in these regions, which normally leads to an insufficient accumulation of moisture in the soil profile particularly during the growing season. Thanks to the large soil water-holding capacity of alluvial soils, their relative moisture deficit is high when compared to the lighter loamy, or sandy soils that are typically found along the edges of river beds. To interpret results of the rPDSI and rZ-index locally (particularly in the case of alluvial soils), we must also bear in mind that the applied methods do not consider the effects of a high water table, which can be important in many cases and can change the water balance at the individual sites as well as the ability of plants to extract water from the soil. The rZ-index maps (fig. 5(c) and (d)) indicate that due to the lower temperatures and different soil characteristics the central highland region of the country is generally much less susceptible even to short-term drought events when compared to the 1-month SPI, which takes into account only the precipitation amount and distribution. The low probability of severe drought events in the border mountain chains and the central highlands is of particular importance as it decreases the region's overall vulnerability to large-scale droughts. This is due to the fact that these regions contain the main reservoirs and spring areas of major rivers (e.g., Elbe) that provide water supplies to the lowland—and in most cases, the more drought-prone—regions.

Integration of the four drought indices into a single indicator, i.e., the ICDI (fig. 6(a) and (b)), leads us to the conclusion that from a climatological point of view there are several "epicenters" of drought-prone regions in the Czech Republic. The largest continuous area with a high risk of drought occurrence (more than 60% of months within dry spells) is found in the southeastern part of the country with a secondary additional "epicenter" close to the border with Slovakia. Other drought-vulnerable regions are found in the lowlands of the Elbe river valley and in the area on the lee side of the Krušné Hory Mountains in the western part of the country. During the warm season (April–September) the spatial extent of the high-risk area increases and the fragmented "epicenters" tend to create continuous entities. On the contrary, the mountain ranges (on the border with Germany, Slovakia, Austria, and Poland) as well as the Bohemian-Moravian Highlands in the center of the country are only rarely influenced by drought. Besides the high altitude areas, the lowlands in the upper northeastern reaches of the country are among those regions that are only marginally endangered by drought events when compared to the rest of the country due to higher precipitation. We have found that almost two-thirds of the country falls within regions where drought occurs less than one-third of the time. Drought events in these regions are typically short with only a very low chance of prolonged dry episodes that are so typical of the drought "epicenters." The ICDI concept proved to be useful at the decision-making level (e.g., to initially determine the most drought-prone administrative regions) as was noted by Brázdil (2007). Information of this type could be much easier utilized by decision makers as it is robust and straightforward, and when calculated for existing administrative units it is also more applicable.

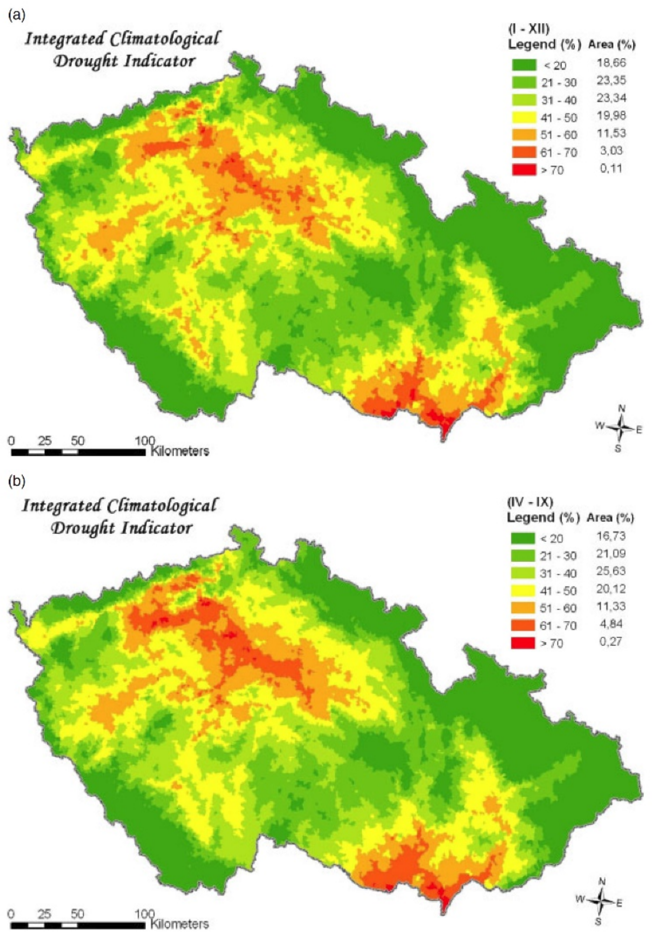


Figure 6. Proportion of months within a drought episode according to the ICDI-based data from (a) all months (January–December) and (b) months in the warm season (April–September). The ICDI integrates results from the 1- and 3-month rSPI, rZ-index, and rPDSI and is calculated as a mean value for each cadastre unit.

3.3. Regionalization of drought characteristics

The regionalization process used in determining drought characteristics was performed according to the Ward's method algorithm using results of the 1- and 3-month rSPI, rZ-index and rPDSI calculations. We used the number of drought events, their mean and maximum duration and number of months within drought episodes in individual seasons according to individual drought indices used as the input variables. The process behind any cluster analysis is a step-by-step aggregation during which two groups are merged each time the algorithm is iterated based on the value of the chosen metric. The key aspect of the analysis is to decide that the simplest and most admissible configuration of groups was reached (Lana and Burgueňo, 1998). If we repeat the procedure indefinitely we obtain one solution including all climatic stations classified within the same cluster. Nevertheless, if we chart the consecutive values of the similarity metric (i.e., in our case the squared Euclidian distance) we can assume that the aggregation previous to a sharp increase in this indicator is the simplest acceptable configuration. Figure 7 shows this evolution for the last 50 clusters in the examined dataset. We can observe a clear change in the indicator value if we attempt a reduction from six to five cluster groups, and thus, we decided to define six station groups according to their drought characteristics.

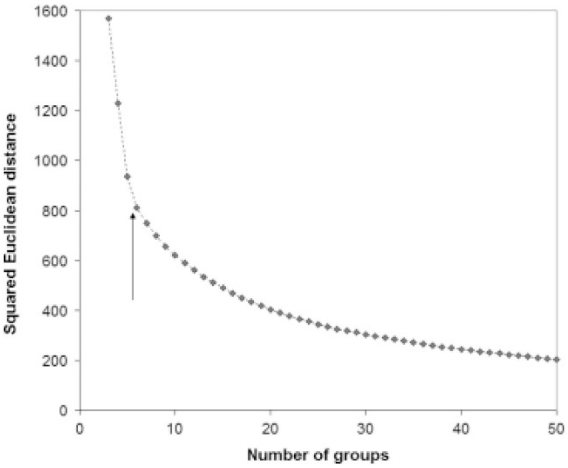


Figure 7. Evolution of the similarity metrics (squared Euclidean distance) with the number of attempted groups. The arrow indicates a sudden change of the indicator value.

Figure 8 schematizes the resulting regionalization with each station being represented by the corresponding cluster number. Table II provides an insight into the number of drought events, mean drought-spell duration, and the basic climatological parameters of each cluster group. The climatic stations classified in Cluster 1 cover the warmest areas with the lowest precipitation located mostly on heavy soils. They are characterized by numerous short-term drought events indicated by the 1-month rSPI and rZ-index. In the same period, the rPDSI signals a persistent soil moisture deficit throughout most of the observational period. Cluster 2 stations are within close proximity of the previous group and are described by a high number of drought events having a shorter duration than those within Cluster 1. The remaining lowland stations with higher precipitation totals and lower soil water-holding capacities represent Cluster 3 stations. Drought-prone stations are almost exclusively situated in those lowland areas that generally belong to the prime agricultural regions. The Cluster 1 stations are found in regions with elevations less than 250 m, and all stations in Cluster 2 were situated below 300 m. Cluster 3 consists of stations with a considerably higher chance of short-term drought, but with a much lower probability of extended drought periods. From an economical perspective, this region is the most valuable in terms of rain-fed agricultural productivity. Clusters 4 and 5 represent highland areas with relatively ample precipitation and cooler air temperatures, thus seeing only occasional drought spells. Cluster 6 includes 44 stations in the submountainous and mountainous regions (in general above 600 m) that are rarely influenced by short-term droughts and only rarely by long-term drought events with the percentage of months influenced by drought episodes well below 20% compared to over 70 or 60% in the case of Clusters 1 and 2, respectively. Interestingly, in some aspects, this regionalization compares well with results of Kyselý et al. (2007) who grouped stations according to occurrences of their extreme precipitation events. They found that both the southeastern and northwestern regions of the country (represented in our case by Clusters 1, 2, and partially by 3) show a markedly different behavior than those stations found in the highlands (classified as Cluster 4).

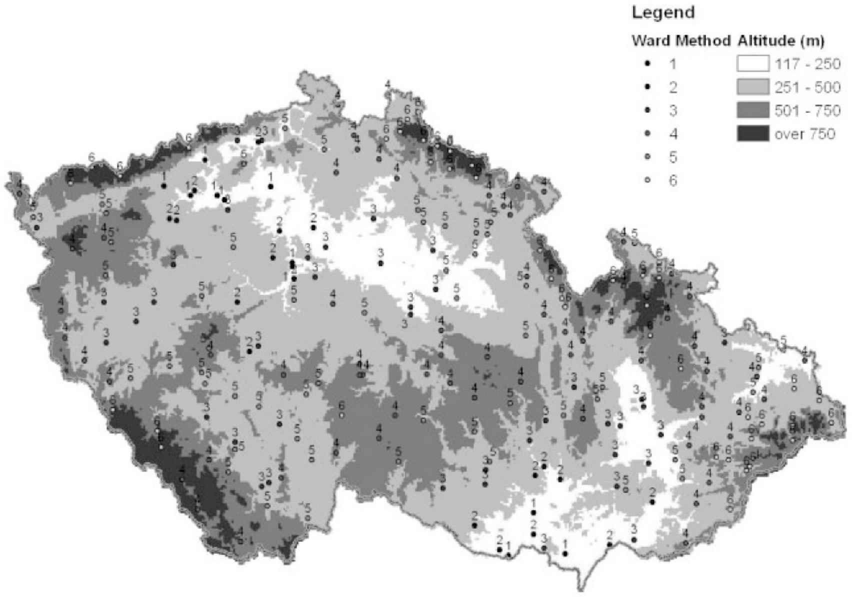
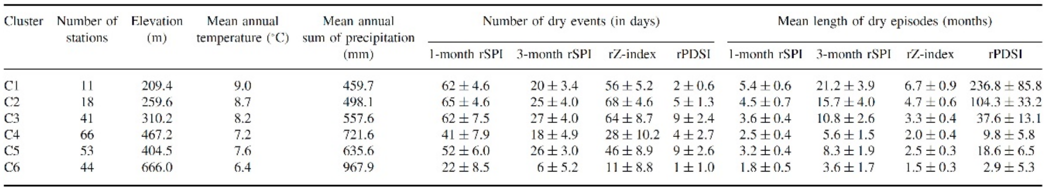


Figure 8. Clusters according to Ward's method of cluster analysis. Shading indicates the altitude of the area while the number depicts an affiliation to a particular group according to table II.

Table II. Cluster centroids and their drought characteristics. The drought climatology characteristics based on rSPI for 1 and 3 months, rZ-index and rPDSI were used as clustering parameters.



Cluster	Number of stations	Elevation (m)	Mean annual temperature (°C)	Mean annual sum of precipitation (mm)	Number of dry events (in days)				Mean length of dry episodes (months)			
					1-month rSPI	3-month rSPI	rZ-index	rPDSI	1-month rSPI	3-month rSPI	rZ-index	rPDSI
C1	11	209.4	9.0	459.7	62 ± 4.6	20 ± 3.4	56 ± 5.2	2 ± 0.6	5.4 ± 0.6	21.2 ± 3.9	6.7 ± 0.9	236.8 ± 85.8
C2	18	259.6	8.7	498.1	65 ± 4.6	25 ± 4.0	68 ± 4.6	5 ± 1.3	4.5 ± 0.7	15.7 ± 4.0	4.7 ± 0.6	104.3 ± 33.2
C3	41	310.2	8.2	557.6	62 ± 7.5	27 ± 4.0	64 ± 8.7	9 ± 2.4	3.6 ± 0.4	10.8 ± 2.6	3.3 ± 0.4	37.6 ± 13.1
C4	66	467.2	7.2	721.6	41 ± 7.9	18 ± 4.9	28 ± 10.2	4 ± 2.7	2.5 ± 0.4	5.6 ± 1.5	2.0 ± 0.4	9.8 ± 5.8
C5	53	404.5	7.6	635.6	52 ± 6.0	26 ± 3.0	46 ± 8.9	9 ± 2.6	3.2 ± 0.4	8.3 ± 1.9	2.5 ± 0.3	18.6 ± 6.5
C6	44	666.0	6.4	967.9	22 ± 8.5	6 ± 5.2	11 ± 8.8	1 ± 1.0	1.8 ± 0.5	3.6 ± 1.7	1.5 ± 0.3	2.9 ± 5.3

3.4. Trend analysis

Analysis of time trends on the precipitation data series at 233 stations showed no statistically significant change during 1961–2000 with the exception of three stations. Consequently, the same findings were repeated when scSPI series for individual stations were evaluated and no prevailing trend (or pattern) toward a drier (or wetter) climate during 1961–2000 was found throughout the territory. On the other hand, we found positive and highly significant trends in the mean air temperatures associated especially with the unusually warm decade of the 1990s for most of the 233 stations that were evaluated. This corresponds with results of the detailed analysis of air temperature series done by Květoň (2001), Huth and Pokorná (2004), or Chládková et al. (2007) as well as with results obtained in the adjacent areas of Poland (Degirmendžič et al., 2004) and the Alps (Casty et al., 2005). As a direct result of increasing temperatures and no change in precipitation, the monthly series of the scZ-index and scPDSI showed decreases, indicating more frequent and/or severe droughts. According to the scZ-index (serving as a short-term drought indicator), 98 stations showed statistically significant negative trends in at least 1 month of the year compared to 26 stations having a positive trend (fig. 9(a) and (b)). The remaining stations showed no statistically significant trend. However, within this group, a large number inclined toward lower scZ-index values with time. This became even more apparent during the warm season (April–September) when more than half the stations showed either statistically significant or at least decreasing scZ-index values with time (fig. 9(b)). The time trends were found to be much more pronounced in the case of the scPDSI, which deals with long-term drought spells compared to shorter spells identified with the scZ-index (fig. 9(c) and (d)). When we evaluated the whole year we found statistically significant trends toward negative scPDSI values at 133 stations with 59 of them having a significant decrease of PDSI in 6 or more months. Interestingly, only 31 stations showed the opposite tendency. During the warm half of the year only 11 stations out of 233 showed a positive trend that was statistically significant in at least 1 month compared to 99 stations showing a negative trend (i.e., tendency to more intensive droughts). Out of the 41 stations with no statistically significant trend, 66% of them still showed a decrease of scPDSI values rather than an increase or no change. Also, in this case, the number of stations with significant drying trends is higher in the eastern Czech Republic. The western part of the country (mainly the areas in the vicinity of Prague and also in the southern Bohemia region) has grown more drought prone during 1961–2000. The stations with positive trends of scPDSI values are found almost exclusively in mountainous areas (e.g., northern border with Poland) as might be seen in figure 9(c) and (d).

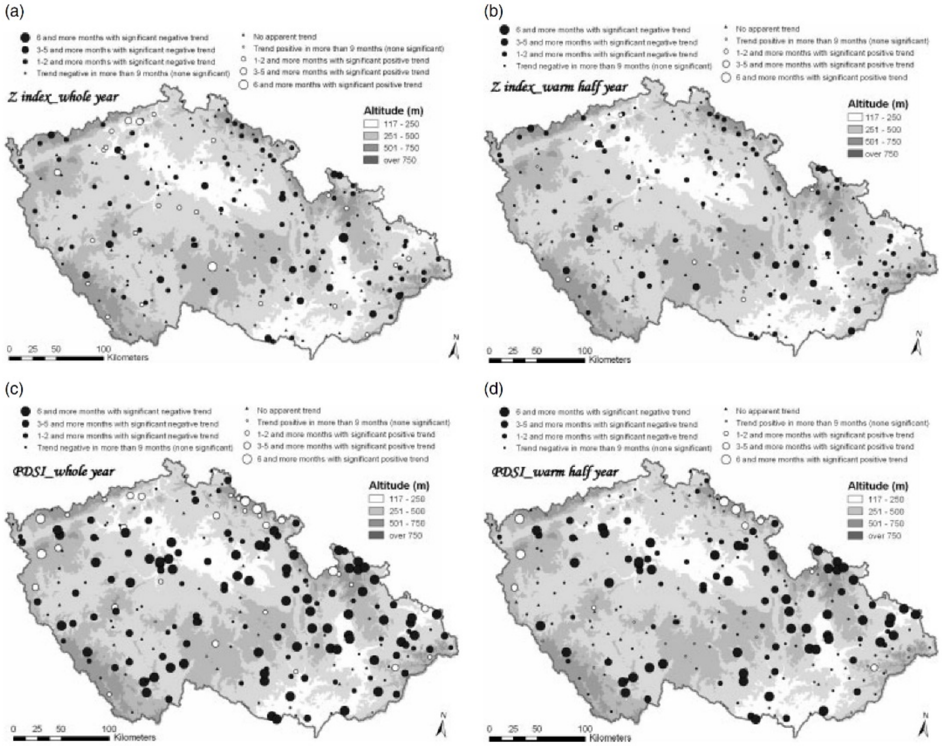


Figure 9. Number of months with statistically significant time trends ($P = 0.05$) of monthly series of the scZ-index (a, b) and scPDSI (c, d) for all months of the year (a, c) and months within the warm season (b, d). The size of the point is proportionate to the number of months with a significant time trend. Shading depicts the altitude of the area.

The fact that the drying trends seem to be more frequent at sites in the eastern part of the country corresponds with the findings of Szinell et al. (1998), who reported regionally specific but significant trends of the scPDSI values toward a drier climate at 15 stations in Hungary, and with Horváth (2002), who reported similar results for the River Tisza catchment. On the continental scale key recent studies differ in their conclusions about the drying trends. Dai et al. (1998), using 2.5° gridded data, noted that areas of severe drought increased in Europe during 1960–1995; however, this rise was found to be of the same magnitude that Europe had already experienced in the early 1920s and late 1940s. In subsequent work applying the PDSI to the 1870–2002 time series, Dai et al. (2004) reported the existence of a notable drying trend since the beginning of the 20th century throughout Europe, which he linked to increasing temperatures over the same time frame. Other studies using a different dataset with higher spatial resolution (0.5° grid) reported only insignificant changes to the areas experiencing moderate to extreme drought conditions during the 20th century (Lloyd-Hughes and Saunders, 2002) or to summer moisture availability across Europe (van der Schrier et al., 2006). However, regardless of uncertainty on the European scale, all the studies discussed indicated very strong drying trends for the area of interest in this paper (i.e., 48–51°N and 13–18°E).

Up to now, only Brázdil (2007) evaluated time trends using scPDSI values using station data having long-term datasets (1850–2003) within this region. They reported a statistically significant trend toward lower PDSI values over the past 153 years ($P = 0.05$) with a mean decrease of values by 0.1 per decade. Analysis of the data showed that there have been two prolonged drought spells of comparable magnitude (1855–1875 and 1970–2003) which corresponds rather well with findings of van der Schrier et al. (2007) in the adjacent Greater Alpine region (GAR). The drying trend between 1900 and 2003 was found to be much stronger when compared to the overall record of 1850–2003 with scPDSI values decreasing by 0.3–0.6 per decade. This study concluded that while the former drought period (i.e., 1855–1875) was caused mainly by a prolonged period of below-normal precipitation, the increase in dryness toward the end of the 20th century can be explained only by increased temperatures that had accelerated especially since the early 1980s. The existence of such a drying trend should be affecting the river discharge in the area. This assumption was indeed confirmed by Majerčáková et al., (1997) and Hisdal et al. (2001) who documented a significant decrease of river flow with time. The latter study, in particular, showed that the southeastern Czech Republic was becoming especially drier, even beyond the overall European trend. We found these results especially troubling because according to Hayes et al. (2005) it is very likely that this trend might be accelerated throughout most of Europe in the upcoming decades thanks to the climate change. When analyzing the above-mentioned results, one should also bear in mind that both the scSPI and scPDSI were used in a monthly time step and that there might be important underlying processes present in shorter timescales. As Brunetti et al. (2002) reported, there seems to be no major change in seasonal or total precipitation amounts, but there has been a substantial trend toward a higher number of dry days during the winter along with an increased intensity of remaining precipitation events, which results in lower soil moisture recharge. In addition to the trends at individual stations, we also investigated trends with regard to the total area experiencing moderate to extreme drought conditions according to the methodology proposed by Lloyd-Hughes and Saunders (2002). Similar to the mentioned study, the area affected by drought spells does not show any statistically significant trend with time unlike the individual series of the scPDSI and scZ-index. It thus seems that despite the fact that the total area of the country experiencing moderate to severe drought at any one time did not change during the 1961–2000 period, there is a tendency toward drought spells becoming more intensive.

4. Concluding remarks

The study introduced an innovation to the standard methodological approaches in evaluating drought climatologies within a particular region, allowing for the identification of drought-prone areas. The analysis relied on well-known and thoroughly tested drought indices (i.e., the SPI, PDSI, and Z-index). These indices were used partly in their original form, and in some cases they were modified to better capture the climatological aspects of drought. In the latter case, each index value was uniquely related to the set of all observations made at all stations during the period 1961–2000 rather than using single site records. Results based on these "relative" indices were combined together to derive an ICDI, which allowed for a more robust multicriteria regionalization of drought risk. The proposed methodology provided an effective and objective quantification of the relative intensity of drought spells, their frequency, and duration with respect to the whole country, thus allowing for an easy identification of the most drought-prone regions. As a part of our drought climatology assessment, the study also described the existing trends in drought-spell occurrences in Central Europe during the last half of the 20th century.

Monthly records of mean temperature and precipitation from 233 Czech stations were used to calculate the original and relative drought indices at all stations. We concluded that more than 3% of the country falls into a high-risk region (defined as over 60% of the months influenced by moderate to extreme drought) and an additional 12.3% is faced with a 50–60% chance of drought according to the rPDSI, rZ-index, and rSPI. Drought probability was found to be clearly linked not only to the precipitation, temperature, and orographic characteristics but also to the soil conditions. The overall outcome of the spatial analysis of drought occurrence was confirmed by the results of a cluster analysis that identified six groups of stations in the Czech Republic according to their drought characteristics. While three clusters represent predominantly dry regions, the mountainous stations, with a relatively limited probability of drought occurrence, were grouped within one homogenous group and the rest of the stations (mostly highland) could be found within two transitional clusters. The results of the cluster analysis might be utilized in selecting the most suitable stations for operational drought monitoring as it clearly identifies stations within the drought "epicenters" that were found in the northwest and southeast.

The analysis of temporal trends showed shifts in drought severity during the last 40 years of the 20th century. While there has been no statistically significant time trend in precipitation anomalies (as described by the scSPI) during the 1961–2000 period, we did find strong decreasing trends in the monthly and long-term water balance deficits expressed by both the scZ-index and scPDSI at many stations, notably located in the eastern part of the country. Over the same time period, only a handful of stations indicated that conditions became wetter. The main reasoning behind these trends was a significant increase of temperatures toward the end of the 20th century. This only adds to the mounting concerns about the potentially higher severity of future drought spells in Central Europe due to expected patterns of climate change. We hope that this study might highlight the drought issue and generate discussion about the potential use of the proposed methodology over the European region while at the same time serving as a useful reference to drought vulnerability over a significant part of Central Europe.

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Appendix A

Table AI. List of 233 stations with monthly temperature and precipitation data for period 1961–2000 used in the study sorted according to longitude.

No.	WMO	Name	Coordinates			Mean annual temperature °C	Mean annual precipitation mm
			Longitude degree (°)	Latitude degree (°)	Altitude meters above the sea level (m)		
1	11 401	Aš	12.21	50.22	700	6.2	728
2	11 407	Františkovy Lázně	12.35	50.12	435	7.1	612
3	11 406	Cheb	12.39	50.07	471	7.4	564
4		Šindelová-Obora	12.59	50.32	587	6.6	882
5	11 423	Poimda	12.68	49.67	742	6.0	696
6	11 413	M.Lázně-vod.	12.69	49.99	691	6.0	783
7	11 411	Potůčky	12.74	50.42	775	5.9	926
8	11 425	Mutěnín	12.74	49.54	480	7.1	695
9	11 415	Karlovy Vary	12.87	50.24	438	7.9	620
10	11 414	Karlovy Vary	12.91	50.20	603	6.5	588
11	11 417	Krásné Údolí	12.92	50.07	642	6.4	603
12	11 428	Domažlice	12.92	49.44	465	8.0	683
13	11 420	Klínovec	12.97	50.39	1244	6.0	983
14	11 419	Konstantinovy Lázně	12.98	49.89	522	6.8	567
15	11 416	Toužim	12.98	50.06	635	6.5	562
16	11 447	Stoíbro	13.00	49.75	412	7.7	510
17	11 451	Staňkov	13.07	49.55	362	7.9	536
18	11 454	Libkov	13.14	49.36	570	7.4	756
19	11 453	Ž.Ruda-Hojsova Stráž	13.20	49.22	867	6.9	1131
20	11 448	Plzeň-Dobřany	13.27	49.68	360	8.1	517
21	11 455	Klatovy	13.30	49.39	430	8.1	597
22	11 438	Kadaň, Tušimice	13.33	50.38	322	8.3	432
23	11 446	Plzeň-Bolevec	13.39	49.79	328	7.5	524
24	11 436	Podbooany	13.41	50.22	332	7.9	457
25	11 437	Blšany	13.47	50.22	290	8.0	452
26	11 432	Nová Ves v Horách	13.48	50.59	725	5.6	788
27	11 442	Kralovice	13.49	49.99	468	7.7	486
28	11 468	Žatec	13.55	50.35	210	9.0	448
29	11 493	Kašperské Hory	13.56	49.15	737	6.2	816
30	11 467	Žatec - Velemyšleves	13.57	50.38	273	8.3	444
31	11 486	Nepomuk	13.58	49.48	429	7.3	618
32	11 457	Churáňov	13.61	49.07	1118	4.3	1084
33	11 433	Kopisty	13.62	50.54	240	8.5	463
34	11 478	Zbiroh	13.75	49.86	480	7.5	585
35	11 466	Lenešice	13.76	50.37	181	8.7	463
36	11 498	Lenora	13.81	48.92	764	5.5	842
37	11 471	Louny	13.82	50.35	230	8.7	469
38		Kocelovice	13.84	49.47	519	7.3	580
39	11 461	Teplice	13.85	50.66	236	8.8	521
40	11 465	Smolnice	13.86	50.31	345	8.1	503
41	11 483	Rožmitál pod Třemšínem	13.86	49.60	524	7.1	622
42	11 488	Blatná	13.88	49.42	420	7.4	562
43	11 484	Vševily	13.89	49.56	577	7.2	645
44	11 491	Strakonice	13.93	49.25	422	8.0	566
45	11 464	Milešovka	13.93	50.55	833	5.3	549
46	11 474	Lány	13.94	50.12	436	7.9	559
47	11 496	Nová Pec	13.96	48.78	753	6.0	777
48	11 497	Husinec	13.99	49.04	536	7.3	639
49	11 503	Ústí nad Labem, město	14.02	50.67	162	9.4	530
50	11 522	Neumětely	14.03	49.85	322	8.3	537
51	11 502	Ústí n.L. Kočkov	14.05	50.68	375	8.5	577
52	11 532	Vráž	14.12	49.38	440	7.8	560

Table AI. (*Continued*).

No.	WMO	Name	Coordinates			Mean annual temperature °C	Mean annual precipitation mm
			Longitude degree (°)	Latitude degree (°)	Altitude meters above the sea level (m)		
53	11 543	Lhenice	14.15	48.99	558	7.6	647
54		Doksany	14.17	50.45	158	8.7	449
55	11 537	Vodňany	14.17	49.15	395	7.9	549
56	11 539	Chelčice	14.18	49.11	466	7.9	583
57	11 527	Solenice	14.18	49.61	359	8.1	523
58	11 501	Děčín	14.21	50.76	157	8.4	649
59	11 525	Kamýk nad Vltavou	14.25	49.64	275	8.0	530
60	11 518	Praha 6, Ruzyně	14.26	50.10	364	8.0	510
61	11 510	Kralupy nad Vltavou	14.29	50.24	220	8.5	473
62	11 533	Olešná	14.31	49.34	452	7.6	546
63	11 549	Vyšší Brod	14.32	48.65	559	6.5	725
64	11 515	Praha, Klementinum	14.42	50.09	191	10.2	464
65	11 519	Praha, Karlov	14.42	50.07	232	9.6	437
66	11 541	Planá	14.42	48.94	420	8.0	602
67	11 520	Praha, Libuš	14.45	50.01	303	8.9	523
68	11 528	Nadějkov	14.47	49.52	615	6.9	654
69	11 571	Jílové u Prahy	14.47	49.90	424	8.1	615
70	11 542	Eeské Budějovice	14.47	48.97	388	8.4	587
71	11 595	Oímov	14.48	48.85	474	7.6	609
72	11 535	Bechyně	14.49	49.27	442	7.5	556
73	11 567	Praha, Kbely	14.54	50.12	282	8.6	532
74	11 562	Tišice	14.55	50.28	168	8.9	508
75	11 554	Eeská Lípa	14.55	50.68	252	8.1	626
76	11 591	Rudolfov-Jivno	14.56	49.00	559	7.5	666
77	11 551	Varnsdorf	14.61	50.91	365	7.8	792
78	11 560	Praha, Uhoíněves	14.61	50.03	299	8.7	575
79	11 585	Borkovice	14.64	49.21	419	7.4	598
80	11 563	Brandýs nad Labem	14.66	50.19	179	9.1	571
81	11 582	Tábor	14.67	49.44	461	7.7	571
82	11 558	Doksy	14.67	50.57	284	7.9	659
83	11 581	Hlasivo	14.75	49.50	540	7.3	605
84	11 552	Jablonné v Podještědí	14.77	50.77	320	7.4	728
85	11 589	Třeboň	14.77	49.11	423	7.7	613
86	11 572	Ondřejov	14.78	49.91	485	7.6	666
87	11 593	Byňov	14.81	48.81	475	7.4	657
88	11 557	Stráž pod Ralskem	14.81	50.70	310	7.2	665
89	11 635	Jindřichův Hradec	14.96	49.16	525	7.3	661
90	11 583	Černovice	14.96	49.35	586	7.0	765
91	11 556	Český Dub	14.99	50.66	315	7.2	793
92	11 600	Andělka	14.99	51.00	298	7.8	702
93		Semčice	15.01	50.36	234	8.8	581
94	11 603	Liberec	15.03	50.77	398	7.4	816
95	11 578	Staňkovice, Nová Ves	15.04	49.88	415	8.1	618
96	11 627	Čechtice	15.05	49.62	490	7.6	711
97	11 628	Křešín, Kramolín	15.06	49.57	550	7.4	638
98	11 628	Košetice	15.08	49.57	534	7.5	638
99	11 617	Poděbrady	15.11	50.14	196	9.1	585
100	11 602	Bedřichov	15.13	50.82	777	4.8	1230
101	11 610	Turnov	15.15	50.58	252	7.9	679
102	11 608	Hejnice	15.18	50.88	396	7.6	973
103	11 604	Nové Město pod Smrkem	15.25	50.93	525	7.1	1054
104	11 634	Počátky	15.27	49.26	647	6.6	675
105	11 605	Desná	15.32	50.79	772	4.8	1348
106	11 609	Jičín	15.35	50.44	283	7.7	661
107	11 632	Nový Rychnov	15.37	49.39	624	6.8	716

Table AI. (*Continued*).

No.	WMO	Name	Coordinates			Mean annual temperature °C	Mean annual precipitation mm
			Longitude degree (°)	Latitude degree (°)	Altitude meters above the sea level (m)		
108	11 624	Chotusice	15.39	49.94	235	8.6	523
109	11 622	Čáslav	15.40	49.91	251	8.8	568
110	11 607	Vysoké nad	15.40	50.68	670	6.1	1006
111	11 615	Slatiny	15.41	50.38	254	7.9	620
112	11 606	Harrachov	15.44	50.77	670	5.3	1278
113		Kostelní Myslová	15.44	49.16	569	7.0	587
114	11 625	Nový Bydžov	15.51	50.24	232	8.3	580
115	11 640	Labská bouda	15.54	50.76	1315	2.7	1371
116	11 640	Vítkovice	15.54	50.75	1410	2.7	1394
117	11 644	Benecko	15.56	50.66	880	5.1	1024
118	11 619	Přelouč	15.57	50.05	209	8.4	594
119	11 612	Holovousy	15.58	50.37	321	8.3	663
120	11 656	Havlíčkův Brod	15.58	49.61	455	7.4	671
121	11 662	Jihlava	15.59	49.38	550	6.8	586
122	11 650	Dobřenice	15.63	50.15	230	8.4	602
123	11 620	Seč	15.65	49.84	529	7.8	786
124	11 655	Chotěboř	15.67	49.72	519	7.4	725
125	11 643	Pec pod Sněžkou	15.73	50.69	816	5.2	1237
126	11 652	Pardubice	15.74	50.01	225	8.5	601
127	11 659	Přibyslav	15.76	49.58	530	6.8	675
128	11 641	Janské Lázně	15.78	50.63	650	5.8	1035
129	11 667	Moravské Budějovice	15.81	49.05	457	7.8	531
130	11 678	Velichovky	15.83	50.36	299	8.0	642
131	11 648	Hradec Králové, Pouchov	15.84	50.25	243	8.2	597
132	11 645	Trutnov	15.90	50.55	437	6.9	756
133	11 647	Jaroměř	15.92	50.35	263	8.0	647
134	11 646	Dvůr Králové nad Labem	15.93	50.42	340	7.6	675
135	11 660	Vatín	15.97	49.52	555	6.9	640
136	11 687	Velké Meziříčí	16.00	49.35	452	7.3	586
137	11 675	Úpice	16.02	50.51	413	7.1	707
138	11 683	Svratouch	16.03	49.74	737	5.9	766
139	11 673	Červený Kostelec	16.08	50.46	410	7.1	748
140	11 698	Kuchařovice	16.08	48.88	334	8.6	473
141		Adršpach	16.11	50.61	510	6.6	811
142	11 692	Sedlec	16.12	49.17	473	7.6	528
143	11 693	Dukovany	16.13	49.09	400	8.0	499
144	11 691	Náměšť nad Oslavou	16.14	49.21	387	7.7	552
145	11 686	Bystřice nad Pernštejnem	16.25	49.52	573	6.7	591
146	11 680	Rychnov nad Kněžnou	16.27	50.16	335	7.7	696
147	11 677	Doudleby nad Orlicí	16.27	50.12	310	7.8	683
148	11 696	Dyjákovice	16.29	48.77	201	9.2	469
149	11 681	Litomyšl	16.31	49.87	351	8.1	678
150	11 685	Nedvězí	16.31	49.63	722	6.0	698
151	11 671	Broumov	16.33	50.60	405	7.1	677
152	11 674	Deštné v Orlic. horách	16.35	50.30	635	5.5	1196
153	11 696	Hevlín	16.37	48.75	180	9.2	473
154	11 689	Tišnov	16.43	49.34	275	8.1	552
155	11 679	Ústí nad Orlicí	16.43	49.98	557	7.3	760
156	11 676	Rokytnice v Orlic.horách	16.46	50.17	564	6.8	930
157	11 695	Troubsko	16.50	49.17	278	8.6	517
158	11 724	Pohořelice nad Jihlavou	16.52	48.98	183	9.2	470
159	11 729	Brod nad Dyjí	16.54	48.87	175	9.2	483
160	11 665	Lysice	16.54	49.45	355	7.7	594
161	11 682	Nekoř	16.56	50.07	488	7.0	847
162	11 721	Brno, Žabovoesky	16.56	49.22	235	8.9	515

Table AI. (*Continued*).

No.	WMO	Name	Coordinates			Mean annual temperature °C	Mean annual precipitation mm
			Longitude degree (°)	Latitude degree (°)	Altitude meters above the sea level (m)		
163	11 702	Jablonné nad Orlicí	16.59	50.03	449	7.2	823
164		Lanškroun	16.62	49.91	365	7.3	716
165	11 726	Mikulov	16.63	48.80	220	9.5	519
166	11 715	Boskovice	16.67	49.49	400	7.7	606
167	11 711	Staré Městou	16.68	49.79	408	7.4	676
168	11 723	Brno, Tuřany	16.70	49.16	241	8.9	490
169	11 713	Jevíčko	16.73	49.63	342	7.7	577
170		Hoštejn	16.76	49.87	315	7.3	759
171	11 727	Lednice	16.80	48.79	176	9.4	488
172	11 716	Protivanov	16.83	49.48	670	6.3	650
173	11 714	Budětsko	16.92	49.58	442	7.5	595
174	11 703	Staré Město-Kunčice	16.95	50.19	658	6.1	1061
175	11 710	Luká	16.95	49.65	510	7.4	601
176	11 705	Šumperk	16.97	49.98	335	7.6	687
177	11 701	Javorník	17.00	50.39	293	7.9	721
178	11 743	Plumlov	17.02	49.47	332	7.9	580
179		Branná	17.04	50.17	647	6.5	813
180		Bernartice u	17.08	50.39	260	7.8	692
181	11 749	Ivanovice na Hané	17.10	49.31	232	8.6	555
182	11 747	Prostějov	17.12	49.46	226	8.3	539
183	11 756	Hodonín	17.13	48.86	180	9.3	526
184	11 757	Brankovice	17.14	49.16	268	8.4	549
185	11 731	Jeseník	17.18	50.23	660	6.9	937
186	11 753	Stříłky	17.21	49.14	341	8.5	618
187	11 735	Praděd	17.23	50.08	1490	6.7	1161
188	11 741	Paseka	17.23	49.80	375	7.9	672
189		Olomouc- Kl. Hradisko	17.27	49.61	215	8.4	557
190	11 737	Rýmaýov	17.28	49.93	597	6.0	786
191	11 742	Olomouc - Holice	17.28	49.57	210	8.8	557
192		Mikulovice	17.30	50.30	418	7.1	875
193	11 732	Zlaté Hory	17.31	50.23	757	6.9	1014
194	11 755	Strážnice na Moravě	17.31	48.90	187	9.1	527
195	11 751	Kroměříž	17.37	49.29	235	8.8	574
196		Zlaté Hory	17.40	50.26	405	7.1	854
197	11 736	Světlá Hora	17.40	50.03	593	6.2	725
198	11 754	Staré Město	17.42	49.09	235	8.9	539
199	11 748	Přerov-letiště	17.44	49.44	205	8.4	591
200	11 766	Červená	17.54	49.78	750	5.6	744
201	11 761	Město Albrechtice	17.56	50.15	483	7.5	754
202	11 774	Holešov	17.57	49.32	224	8.6	624
203	11 775	Zlín	17.64	49.23	261	8.7	666
204	11 764	Bohdanovice	17.64	49.90	430	7.2	633
205	11 771	Bystřice pod Hostýnem	17.67	49.40	317	8.5	725
206	11 779	Strání	17.71	48.90	385	7.9	811
207		Střítěž nad Ludinou	17.74	49.60	332	7.9	697
208	11 768	Hranice	17.74	49.55	259	8.2	682
209	11 767	Vítkov	17.75	49.78	482	7.2	711
210	11 778	Luhačovice	17.77	49.11	297	8.3	742
211	11 777	Vizovice	17.85	49.22	315	8.0	721
212	11 763	Opava	17.87	49.93	272	8.2	593
213	11 770	Hošt'álková	17.89	49.35	385	7.8	885
214	11 769	Valašské Mezioíčí	17.98	49.46	334	8.0	768
215	11 788	Vsetín	17.98	49.34	340	7.4	810
216	11 780	Brumov-Bylnice	18.03	49.09	350	8.1	786
217		Nový Jičín	18.03	49.59	284	7.8	776
218		Ženklava	18.10	49.57	330	7.7	848
219	11 789	Huslenky	18.12	49.30	450	7.3	880

Table AI. (*Continued*).

No.	WMO	Name	Coordinates			Mean annual temperature °C	Mean annual precipitation mm
			Longitude degree (°)	Latitude degree (°)	Altitude meters above the sea level (m)		
220	11 782	Mošnov	18.13	49.70	250	8.4	702
221		Klimkovice	18.14	49.78	250	8.1	707
222	11 786	Rožnov pod Radhoštěm	18.14	49.46	370	7.6	878
223		Halenkov	18.15	49.32	427	7.3	880
224		Ostrava-Poruba	18.15	49.82	242	8.3	708
225		Fryčovice	18.21	49.66	274	7.8	813
226		Frenštát pod Radhoštěm	18.22	49.54	410	7.8	984
227	11 781	Bohumín	18.33	49.92	199	8.7	681
228	11 784	Lučina	18.44	49.73	300	8.2	833
229	11 787	Lysá hora	18.45	49.54	1322	2.8	1407
230		Staré Hamry	18.46	49.47	535	5.5	1077
231	11 795	Karviná	18.51	49.88	219	8.4	768
232	11 799	Týinec	18.65	49.68	300	7.6	949
233	11 792	Jablunkov	18.75	49.58	401	7.6	988
Mean of 233 stations					434.6	7.54	687.9
Mean of the Czech Republic					430.0	7.50	674.0

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