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Long-term variability of droughts in the Czech Lands and large-scale climate drivers

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Abstract. While a considerable number of records document the temporal variability of droughts for central Europe, understanding of its underlying causes remains limited. In this contribution, time series of three drought indices (SPI, SPEI, PDSI) that may be used to characterize the long-term drought regime of the Czech Lands are analyzed with regard to their mid-to-long-term variability and potential links to external and internal climate forcings over the 1501–2006 period. Employing instrumental and proxy-based data characterizing the external climate forcings (solar and volcanic activity, concentration of greenhouse gases) in parallel with series that correspond to the activity of climate variability modes with pronounced inter-annual to inter-decadal variability (El Niño–Southern Oscillation – ENSO, Atlantic Multidecadal Oscillation – AMO, Pacific Decadal Oscillation – PDO), regression and wavelet analysis were deployed to identify and quantify the temporal variability patterns of drought indices and similarity between individual signals. Aside from the long-term trend that correlates with anthropogenic radiative forcing, temperatures in the AMO and PDO regions were disclosed as one of the possible drivers of inter-decadal variability in the Czech drought regime. Colder and wetter episodes were found to coincide with increased volcanic activity, while no clear signature of solar activity was found. In addition to identification of the links themselves, their temporal stability and coherence were investigated. The oscillations at periods of approximately 60–100 years were found to be potentially relevant in establishing the teleconnections affecting the long-term variability of central European droughts.

1 Introduction

Droughts, among the most prominent manifestations of extreme weather and climate anomalies, are not only of great climatological interest but also constitute an essential factor to be considered in the assessment of the impacts of climate change (Stocker et al., 2013; Trnka et al., 2018; Wilhite and Pulwarty, 2018). The abundance of long-term instrumental meteorological observations in the European area has provided a basis for a number of recent drought-focused studies, revealing complex regional drought patterns and a richness of features observed at various spatial and temporal scales (e.g., van der Schrier, 2006, 2007; Brázdil et al., 2009; Briffa et al., 2009; Dubrovský et al., 2009; Sousa et al., 2011; Spinoni et al., 2015). Along with more rapid variations, these also include long-term variability, such as a distinct trend towards drier conditions, prominent especially during the late 20th and early 21st centuries (e.g., Trnka et al., 2009a; Brázdil et al., 2015b).

In addition to a substantial number of Europe-centered studies investigating instrumental-period drought indices, generally calculated from measured precipitation totals and temperatures, considerable attention has been devoted to pre-instrumental drought reconstructions. The longest high-resolution drought series are typically based on various tree-ring series, usually reconstructing drought indices (mainly PDSI) for summer (JJA) or other combinations of months during the growing season (e.g., Büntgen et al., 2010a, 2010b, 2011a, 2011b; Cook et al., 2015; Dobrovolný et al., 2015). Natural proxy data (see PAGES Hydro2k Consortium, 2017) may be supplemented by the documentary records generally utilized in historical climatology (Brázdil et al., 2005, 2010) in drought reconstructions. These are usually represented as series for drought frequency covering the last few centuries, usually from the 16th century to the present time or shorter (e.g., Piervitali and Colacino, 2001; Domínguez-Castro et al., 2008, 2012; Diodato and Bellocchi, 2011; Brázdil et al., 2013; Noone et al., 2017). However, reconstructions of long-term series of drought indices from documentary and instrumental data, as has been done for the Czech Lands from the 16th century (Brázdil et al., 2016a; Možný et al., 2016), still remain the exception.

Although the series above permit the study of drought variability at various temporal and spatial scales, only a few researchers have attempted to link such fluctuations with the effects of external and internal forcings, usually within the instrumental period. Pongrácz et al. (2003) applied a fuzzy-rule-based technique to the analysis of droughts in Hungary. Hess-Brezowsky circulation types and ENSO events were used and their influence on drought occurrence (monthly PDSI) documented. Trnka et al. (2009b) showed (using weekly Z-index and PDSI) that increase in drought frequency toward the end of the 20th century during April–June period is linked to increased occurrence of Hess-Brezowsky circulation types that are conducive to drought conditions over central Europe. Brázdil et al. (2015a) used regression analysis to investigate the effects of various external and internal forcings in series of drought indices in the Czech Lands during the 1805–2012 period. They demonstrated the importance of the North Atlantic Oscillation phase and of the aggregate effect of anthropogenic forcings. Other examples include attribution analyses for the climatic variables in Croatia (Bice et al., 2012) and for temperature and precipitation instrumental series in the Czech Lands (Mikšovský et al., 2014). More recent papers addressing the influence of certain forcing factors on individual climate variables may be added to this overview (e.g., Anet et al., 2014; Gudmundsson and Seneviratne, 2016; Schwander et al., 2017). Even so, the exact causes of the variability detected in drought data remain only incompletely known, especially regarding variations at decadal and multidecadal time scales.

The current paper focuses on the identification and quantitative attribution of drought variability expressed by series of three drought indices in the Czech Lands (modern Czech Republic) throughout the past five centuries (1501–2006), with the emphasis on manifestations of inter-decadal changes and their possible drivers. Regression and wavelet analysis were employed (see Section 3) to identify links between series of the three drought indices (supplemented by corresponding temperature and precipitation series) and the activity of external climate forcings or internal climate variability modes (see Section 2). The results of these analyses are presented in Section 4 and discussed with respect to the effects and variability patterns of individual forcings and their interaction in Section 5. The last section then delivers a number of concluding remarks.

2 Data

2.1 Drought indices

Various drought indices are used to characterize the spatio-temporal variability of droughts (see e.g. Heim, 2000). To capture the temporal patterns of historical Czech drought regime, three drought indices were employed, each of them embodying a different strategy for defining dry/wet conditions:

(i) Standardized Precipitation Index (SPI; McKee et al., 1993), calculated as the standardized deviation of precipitation totals over chosen time-window from their long-term means. SPI is a purely precipitation-based drought descriptor that takes no account of the direct influence of temperature. As such, it is primarily representative of the factors altering precipitation in the target area.

(ii) Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010) is an index similar to SPI, but it considers potential evapotranspiration rather than precipitation alone, hence also reflecting temperature-related climate variations.

(iii) Palmer Drought Severity Index (PDSI; Palmer 1965) describes long-term soil moisture status. A self-calibrated version of PDSI was used in this contribution (Wells et al., 2004). Unlike SPI and SPEI, which are calculated from contemporaneous values of precipitation/temperature, PDSI also considers past drought status and effectively also storage capacity of the soil, thereby providing a better reflection of long-term drought behavior.

Long-term seasonal and annual series of these three indices, dating from AD 1501 in the Czech Lands (Brázdil et al., 2016a) were used in the current study. They were derived from 500-year temperature and precipitation reconstructions based on a combination of documentary data and instrumental measurements. Firstly, Dobrovolný et al. (2010) reconstructed monthly, seasonal and annual central European temperature series, partly based on temperature indices derived from documentary data for Germany, Switzerland and the Czech Lands in the 1501–1854 period and partly on homogenized instrumental temperature series from 11 meteorological stations in central Europe (Germany, Austria, Switzerland, Bohemia) from 1760 onwards. This temperature series is fully representative of the Czech Lands. Subsequently, seasonal and annual precipitation series for the Czech Lands were reconstructed from document-based precipitation indices in the 1501–1854 period and from mean precipitation series calculated from measured precipitation totals in the Czech Lands after 1804 (Dobrovolný et al., 2015).

Missing monthly precipitation figures in the Dobrovolný et al. (2015) pre-1804 reconstruction obstructed the creation of a corresponding series of drought indices for the Czech Lands dating back to AD 1501. To ameliorate this, Czech mean monthly precipitation series for the 1875–1974 instrumental period were used to estimate the likely distribution of monthly precipitation totals in any given season. This resulted in a 100-member ensemble of monthly precipitation totals for every season and year in 1501–1803, dividing the seasonal precipitation according to the shares of recorded monthly precipitation in individual years during the 1875−1974 period. Using a median value of a hundred monthly realizations up to 1803 and combining them with the measured totals for 1804–2015, a monthly precipitation series for calculation of Czech drought indices series was obtained (Brázdil et al., 2016a). Note that only seasonal and annual series of Czech SPI, SPEI and PDSI (Brázdil et al., 2016a), Central European temperature series (Dobrovolný et al., 2010) and Czech precipitation series (Dobrovolný et al., 2015) were employed for further analysis in the current paper.

2.2 Explanatory variables

Due to the multitude of climate-forming agents and the complexity of their interactions, an essential part of statistical attribution analysis consists in the selection of the most relevant explanatory factors and identification of the most appropriate quantifiable descriptors of their activity. For an analysis involving data from the pre-instrumental period, this task is further complicated by the limited amount of data suitable for direct quantitative analysis. Even so, reconstructions of long-term behavior exist for most of the key climate drivers, be they external forcings or major modes of internal variability. In this analysis, several of these data sources were considered; brief descriptions of them appear below, while visualization of their fluctuations is provided in Figs. 2 and 3, supplemented by wavelet spectra for the signals with notable oscillatory components in Fig. 6.

Of the external factors shaping the long-term climate evolution, a key role is played by the effects modifying radiative balance through changes in atmospheric composition. While the respective processes are quite complex and involve gaseous atmospheric components as well as aerosols, a large part of the observed changes may be attributed to variations in the concentrations of long-lived greenhouse gases, carbon dioxide (CO_2) in particular (Stocker et al., 2013). Considering that past CO_2 concentrations are accessible to relatively accurate reconstruction using ice cores, their annual values were considered as a potential formal descriptor of the long-term trends in the drought series studied here. The time series of annual CO_2 concentrations, compiled by the Earth Policy Institute from historical data by the Worldwatch Institute and from observations by NOAA, was obtained from the CLIMEXP database (https://climexp.knmi.nl/).

While variations in solar activity typically leave no strong clear imprint on the climatic conditions of the lower troposphere during the instrumental era (e.g., Benestad, 2003; Gray et al. 2010; Brönnimann, 2015), their effects may become more noticeable over longer analysis periods, with major events such as the Maunder Minimum coming into play (e.g., Lohmann et al., 2004). In this contribution, a reconstruction of annual mean total solar irradiance since AD 1610 based on numbers of sunspots (Coddington et al., 2016) was used as the descriptor of solar activity. Since annual solar activity data for the earliest part of the period analyzed were not available, the tests involving solar forcing were carried out for a shorter interval, covering the years 1610–2006.

Unlike variations in solar activity or concentrations of greenhouse gases, the effects of major volcanic eruptions tend to be rather episodic, manifesting in the lower troposphere as temporary global temperature drops (e.g. Canty et al., 2013), but with rather inconclusive local imprints during the instrumental period (e.g. Mikšovský et al., 2016a). In this study, the volcanic activity descriptor was adapted from the stratospheric volcanic aerosol optical-depth series in the 30°N–90°N latitudinal band compiled by Crowley and Unterman (2013), based on sulfate records in the polar ice cores.

Aside from being the dominant climate mode in the equatorial Pacific, El Niño–Southern Oscillation (ENSO) has also been linked to various aspects of weather patterns in many regions around the globe (e.g., Brands, 2017 and references therein). While these teleconnections manifest quite weakly in the European climate, some indications of an ENSO imprint have been found in Czech temperature series (Mikšovský et al., 2014) as well as in the drought indices themselves (Brázdil et al., 2015a). Two ENSO reconstructions were employed here: a reconstruction of inter-annual ENSO variability based on tree rings by Li et al. (2011) and a multi-proxy reconstruction of temperature in the Niño3 region by Mann et al. (2009). Since the primary focus of this study centers upon oscillatory behavior associated with internal climate variability, the Mann et al. series has been detrended by subtracting the 70-year moving average of the northern hemisphere mean temperature, also provided by Mann et al. (2009); the largely trend-free series by Li et al. (2011) was used in its original form. Even after detrending, the difference in the basic nature of the temporal variability of both ENSO-capturing signals was profound (Fig. 3). While the data from Mann et al. (2009) reflect largely inter-decadal variations, the ENSO signal by Li et al. (2011) only involves more rapid variations. This contrast also appears in the wavelet spectra in Fig. 6, with the Li et al. series dominated by oscillations within a range usually associated with ENSO activity during the instrumental era (*c*. 2–8 years – e.g., Torrence and Compo, 1998), while the Mann et al. reconstruction is active largely in the range of 8–20-year periods.

In the area of northern Atlantic, the Atlantic Multidecadal Oscillation (AMO) provides the major source of inter-decadal variability, with an assumed main periodicity of about 70 years (e.g., Enfield et al., 2001). To analyze possible AMO influence over the last five centuries, a reconstruction of annual temperatures in the AMO region by Mann et al. (2009) was employed. Again, due to the presence of a strong trend component in the time series involved, detrending by moving mean of the northern hemispheric temperature was applied during the pre-processing phase. The same treatment was also used in the case of the Pacific Decadal Oscillation (PDO), utilizing Mann et al. (2009) temperature data for the northern Pacific region. It is essential to note that this procedure does not fully conform to the usual definition of the PDO index, which is typically derived from the first principal component of sea surface temperatures in the northern Pacific, detrended by mean global sea temperature. For the sake of brevity, however, the PDO designation will hereafter be used for the signal obtained from Mann et al. (2009) data.

3 Methods

Despite the inherently nonlinear nature of many processes and interactions within the climate system, the constraints imposed by limited data availability and quality often render the use of nonlinear techniques impractical, even worthless, given their higher degrees of freedom and higher sensitivity to inhomogeneities in the inputs. This issue may become still more critical for non-instrumental data sources, often already burdened with substantial uncertainty and homogeneity problems. For this reason, only relatively robust linear analytical methods – multiple linear regression and wavelet analysis – were employed here.

Multiple linear regression was used to separate and quantify individual components in the series of drought indices, formally pertaining to individual explanatory variables. The statistical significance of the regression coefficients was evaluated by moving-block bootstrap, with the block size chosen to account for autocorrelations within the regression residuals (Politis and White, 2004). The results are presented in the form of standardized regression coefficients in Figs. 4 and 5, i.e. equivalent to a setup with both predictand and predictor series converted in linear fashion to zero mean and unit variance. The series were analyzed in the annual time step, either as true annual means, or as sequences of values pertaining to a single season in the usual climatological sense (the seasonal analysis was only carried out for SPI and SPEI indices, since PDSI definition involves long-term memory). Because of the availability of annually-resolved solar irradiance data and their possible aliasing with the forcing effects of greenhouse gases, the target period was restricted to the years 1610–2006 for the investigation of solar and CO_2-related effects; the rest of the analyses were carried out for the whole 1501–2006 period. To investigate possible instabilities in the relations detected, regression analysis was also carried out for the sub-periods 1501 (or 1610) to 1850 and 1851 to 2006 (here considered approximately equivalent to the instrumental period). No time-lag was applied to the predictors, except in the case of volcanic forcing at seasonal time scales, when a delay of three months was applied.

Continuous wavelet transform, based on the Morlet-type mother wavelet, was employed to obtain a better picture of oscillatory components in the series of drought characteristics and explanatory variables. By providing transformation of the target signals into time-frequency domains, the wavelet approach facilitates the investigation of (in)stability in the oscillatory components of the target signals and, through cross-wavelet spectra, their mutual coherence. This makes it possible to identify sub-periods of activity associated with oscillations of interest, and their eventual similarity (and potential transfer) between individual signals. The statistical significance of the wavelet coefficients was evaluated against the null hypothesis of a series generated by an autoregressive process of the first order (AR1), using the methodology described by Torrence and Compo (1998). Standardized and bias-corrected coefficients are presented for the wavelet (Liu et al., 2007) and cross-wavelet (Veleda et al., 2012) spectra.

4 Results

4.1 Drought responses to forcings

Standardized regression coefficients obtained by multiple linear regression between series of Czech drought indices, temperature or precipitation and a set of explanatory variables, representing external forcings and large-scale internal climate variability modes, are shown for annual values in Fig. 4 and for seasonal values in Fig. 5. The regression coefficients

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associated with the CO_2 concentration show a clear contrast between the behavior of the Czech temperature (distinct, strongly significant link) and precipitation (statistically non-significant connection) series. This reflects a strong formal similarity in the shape of the temperature series and CO_2 concentration, sharing an increase in the later 20th and early 21st centuries. The connection becomes even more prominent for the 1851–2006 period (Fig. 4c), but does not manifest during the pre-instrumental 1610–1850 era (Fig. 4b), in which the CO_2 signal is mostly featureless. This pattern also appears for individual seasons, with the CO_2–temperature link at its relative strongest during SON and weakest during DJF (Fig. 5). The formal association of CO_2 concentrations with individual drought indices then conforms to their definition: while precipitation-only SPI behaves in a fashion very similar to precipitation itself, stronger (although not always statistically significant) links were indicated for SPEI and PDSI. It is also worthy of note that, due to strong correlation between the respective time series, very similar results would have been obtained if the CO_2 series were replaced with a predictor representing total greenhouse gases forcing or total anthropogenic forcing.

There is a lack of any imprint from solar activity in our target series (Fig. 4). This not only applies to the drought and precipitation data, but also to the temperature, despite the analysis period involving periods of marked decreases in solar irradiance in the form of Maunder and Dalton minima. A similar absence of detectable solar signal was also found for individual seasons (not shown).

The cooling effect of major volcanic eruptions is clear in the Czech temperature series over the entire 1501–2006 period, but becomes statistically non-significant when only the instrumental era (1851–2006) is considered. This contrast may stem from the limited amount of major volcanic events taking place after 1850, combined with the fact that individual eruptions, varied in their location and nature, do not form a sufficiently consistent sample for statistical analysis of local volcanism imprints (unlike, e.g., global temperature, in which the imprint is substantially clearer – see, e.g., Canty et al., 2013). The volcanism effect on Czech precipitation series is non-significant regardless of the period analyzed. As a result, the volcanism-attributed component is negligible in precipitation-only SPI, but somewhat more prominent (even though only borderline significant) in temperature-sensitive SPEI and PDSI. The season-specific outcomes (Fig. 5) are largely consistent with those obtained for the year as a whole, with some degree of cooling indicated for all seasons, thus resulting in mildly wetter conditions following episodes of volcanism reaching the stratosphere.

Despite the previous indications of possible (albeit rather weak) links between the Czech drought regime and the activity of ENSO, this analysis did not reveal any statistically significant associations within the annual data. Such a lack of significant responses was obtained from both ENSO reconstructions (Mann et al., 2009; Li et al., 2011) used herein, despite their distinctly different temporal variability. These results also hold for individual sub-periods. However, in the case of season-specific results, a significant tendency towards higher precipitation (and wetter conditions) was indicated for the positive ENSO phase in DJF for Li et al. (2011) data, as well as a borderline significant tendency towards warmer and drier conditions in SON. No such links appeared when the ENSO reconstruction by Mann et al. (2009) was considered.

The Atlantic Multidecadal Oscillation (AMO) was found to be linked to the variability of Czech precipitation, as well as all drought indices during the 1501–2006 period. However, its effect is largely absent prior to 1850. The existence of a robust link is therefore dubious, especially considering previously reported low AMO influence during the instrumental period (Brázdil et al., 2015b; Mikšovský et al., 2016b). There is a distinct similarity between AMO-related links detected for the annual data and their season-specific counterparts (Fig. 5), with SON showing the highest relative degree of statistical significance.

The imprint of decadal and multidecadal temperature variability in the northern Pacific area, strongly associated with the activity of the Pacific Decadal Oscillation (PDO), was found to be quite distinct in all three drought indices, but especially in PDSI. The influence of PDO is also strong in Czech precipitation data, but less so in central European temperature series. While the relationships are formally stronger for the 1851–2006 period, the link is also borderline significant in the earlier part of the series (1501–1850), especially for PDSI, supporting its temporal stability. On a seasonal basis, the strongest drought association with PDO was indicated for SON, whereas only non-significant links were found for DJF (Fig. 5).

4.2 Coherence between drought indices and forcings

Although Brázdil et al. (2015a) demonstrated well-pronounced inter-annual and inter-decadal variations in the Czech spring–summer drought data, these were predominantly irregular. As follows from Figs. 1 and 6, no persistent, dominant periodic or quasi-periodic component exists in any of the series of the Czech drought indices, or in their temperature or precipitation counterparts. The same also holds when data for individual seasons are studied (not shown). While this finding is not surprising in the context of the central European climate, it also confirms only a limited direct influence for the factors of periodic nature, such as the 11-year solar cycle and the approximately 70-year periodicity of the North Atlantic sea-surface temperature, typically ascribed to AMO (note also that although this periodicity is clearly noticeable in the wavelet spectrum of the AMO series, it tests as statistically significant only from the 18th century onwards – Fig. 6).

Several noteworthy interaction regions in the time-frequency space seem to exist between the Czech climate descriptors and predictors with distinct inter-decadal oscillations, AMO and PDO (Fig. 7). The patterns are very similar for PDO and AMO, following on from the resemblance of the two series. More curious, however, is the similarity between cross-oscillatory patterns pertaining to the relation between AMO/PDO and temperature or precipitation; while some differences appear, the general positions of the areas of significant links are quite alike for both series. None of these regions of significant local coherence is, however, stable throughout the entire period analyzed; coherence within periods of *c*. 20–30 years appears in the 17th and 18th centuries, as well as during most of the 20th century (albeit with a different phase shift). Another region of high coherence appears for periods of about 70 years from the mid-18th century to the end of the 20th. These features also appear in the cross-wavelet spectra involving drought indices (Fig. 7 – results for only SPEI are shown, as the graphs are almost identical for SPI and PDSI).

In contrast to the influence of AMO/PDO, the cross-wavelet spectrum of the Czech climate descriptors *vs*. ENSO reconstruction by Li et al. (2011) shows no significant coherence regions beyond scattered noise. For Mann et al. (2009) data, there are several discontinuous regions in a period band of 8–16 years, but with highly variable phase shifts, indicating the lack of a systematic stable relationship, consistent with the non-significance of the links obtained by the regression analysis.

Cross-wavelet spectra may also shed more light on the interaction between individual explanatory variables (Fig. 7). The similarity between the ENSO representations by Li et al. (2011) and Mann et al. (2009) is concentrated in a period band of *c*. 8–16 years; areas of significant links are, however, quite scattered, with substantial periods of weaker relations. This (together with a lack of shorter-term variations in the Mann et al. data) may explain the differences in regression analysis outcomes for the two ENSO index versions. High coherence is observed between AMO and PDO, especially in the period bands of *c*. 20–30 years and 60–100 years, with relatively stable phase shifts, especially for the latter band. Even in this case, however, significant links exist for only parts of the 1501–2006 period. Finally, there is some direct coherence between the series of temperature and precipitation, mostly appearing around the period of 70–100 years, from the mid-16th to the mid-19th century. However, due to the presence of shorter-term variations in both temperature and precipitation, the occurrence of statistically significant coherences is less prevalent than in the cross-wavelet spectra of temperature/precipitation *vs*. AMO/PDO.

5 Discussion

Brázdil et al. (2015a) analyzed imprints of climate forcings in series of six spring–summer drought indices (SPI-1, SPI-12, SPEI-1, SPEI-12, Z-index and PDSI) for the Czech Lands in the 1805–2012 period. Using multiple regression analysis, they identified the importance of the North Atlantic Oscillation phase and of the aggregate effect of anthropogenic forcing, driven particularly by increasing CO_2 concentrations. However, the magnitude of their effects varied with the type of drought index and season. Among other potential explanatory factors, solar irradiation and the Southern Oscillation showed only minor contributions to drought variability, while the effects of volcanic activity and the Atlantic Multidecadal Oscillation were even weaker and statistically non-significant.

The results obtained from the analysis of three drought indices in the current paper do generally conform to the conclusions of Brázdil et al. (2015a), although there are a few noteworthy contrasts. The general importance of anthropogenic effects in the occurrence and risk of meteorological drought has previously been confirmed by, for example, Gudmundsson and Seneviratne (2016). Based on an observational and climate-model based assessment, they concluded that anthropogenic emissions have increased the probability of drought years in the Mediterranean and decreased it in northern Europe. The evidence related to central Europe appeared inconclusive. This is consistent with increasing drought severity related to temperature rise in southern Europe (Vicente Serrano et al., 2014). More recently, Naumann et al. (2018) demonstrated how drought patterns can worsen in many regions of the world (including southern Europe) at a global temperature increase of 1.5, 2 and 3°C compared with the pre-industrial era. Our findings show that the increase in the ambient CO_2 post 1850 is clearly correlated with the increased probability of drought in the Czech Republic, while during the pre-instrumental period such link does not manifest.

The findings of this study for the effects of solar activity (see Fig. 4) are consistent with previous results targeting the instrumental period and reporting only weak, if any, solar links to the European climate (see e.g. Bice et al., 2012; Mikšovský et al., 2014), or even to global climate descriptors such as global mean temperature (see Benestad, 2003; Gray et al. 2010 for an overview). Despite using a longer period for analysis, involving prominent features of mid-to-long-term solar variability in the form of Maunder and Dalton minima, the absence of significant links suggests that the impacts of solar variations on the drought regime are negligible in central Europe, despite the obvious importance of solar radiation as the main source of the energy for the climate system. On the other hand, Diodato and Bellocchi (2011), studying drought conditions in central-southern Italy in 1581–2007 based on documentary evidence, reported distinct 11-yr and 22-yr cycles, which could reflect single and double sunspot cycles, albeit not consistently present throughout the period analyzed. They even argued that periods of low sunspot activity, such as the Maunder Minimum, could have more impact on drought than local forcing agents. Schwander et al. (2017) studied the influence of solar variability on the occurrence of central European weather types in the 1763–2009 period. They reported fewer days with westerly and west-southwesterly flow over central Europe under low solar activity and an increase in the occurrence of northerly and easterly types. This could be reflected in precipitation totals and droughts as well.

The effects of El Niño–Southern Oscillation (ENSO) on drought variability in central Europe also appear quite limited. Previously, Pongrácz et al. (2003) demonstrated the influence of ENSO events on drought occurrence in Hungary; however the signal was relatively weak in the statistical sense. Bice et al. (2012) showed a weaker influence of ENSO on temperatures in Croatia. Also weaker and less consistent was the ENSO influence on Croatian winter precipitation, modulated by longer-term PDO cycles. Mikšovský et al. (2014) indicated a weak Southern Oscillation influence on Czech temperature series and none on precipitation series. In contrast, Piervitali and Colacino (2001), analyzing drought events derived from rogation ceremonies for the 1565–1915 period in Western Sicily, recorded that a reduction in ENSO events took place in periods when many drought events occurred, and *vice versa*. In the analysis procedure herein, however, the only significant response to ENSO occurred for the DJF season, and only when Li et al. (2011) data were used as the predictor, compared to the non-significant response to the Mann et al. (2009) ENSO series. Considering the absence of shorter-scale variability in the Mann et al. series, it may be speculated that the responses in the seasonal data are tied to inter-annual rather than decadal variability. Specific conclusions regarding the nature and reliability of the respective links are however difficult to make without a supporting analysis of circulation patterns. Furthermore, comparison with prior results obtained for the instrumental period (such as the seasonal variations reported by Brázdil et al. 2015b) is rendered problematic by profound differences in the nature of ENSO-related explanatory variables.

While previous studies of the possible influence of explosive volcanism on Czech droughts reported either no significant connection (Brázdil et al., 2015a), or only a weak and geographically sporadic effect (Mikšovský et al. 2016b), this analysis of more five centuries of data has revealed a more distinct volcanic imprint, suggesting a tendency towards wetter conditions following major eruptions, largely due to temporary temperature decrease. These results are consistent with the findings of Gao and Gao (2017), who analyzed European hydroclimatic responses to volcanic eruptions over the past nine centuries. Applying a superposed epoch analysis, they found a significant wetting response for 31 tropical eruptions (95% confidence level) in years 0 (the year of eruption) and +1 (the first year after eruption) and a significant drying in year +2. Large high-latitude eruptions in the Northern Hemisphere gave rise to drying responses in western–central Europe occurring in year +2 and shifting south-eastwards in years +3 and +4. Similarly, the analysis of the spring and summer hydroclimate over Europe and the Mediterranean during the last millennium by Rao et al. (2017) indicated wet conditions occur in the eruption year and the following three years in western Mediterranean, while northwestern Europe and the British Isles experience dry conditions in response to volcanic eruptions, with the largest moisture deficits in post-eruption years, and the Czech Lands being most affected two and three years after the eruption. Písek and Brázdil (2006) analyzed the imprints of seven large tropical eruptions in four temperature series and three global radiation series in central Europe. They demonstrated that the volcanic signal in regional series is not as strongly expressed as that on a hemispheric scale, owing to varying local effects and circulation patterns. The climatological responses to eruptions in areas closer to central Europe, such as Iceland and the Mediterranean, were identified as more important. This was confirmed by a more recent and detailed analysis of the climatological and environmental impacts of the Tambora 1815 eruption on the Czech Lands (Brázdil et al., 2016b) and in its comparison with the Lakágigar 1783 eruption (Brázdil et al., 2017). Presence of a distinct signature of the Tambora eruption was also confirmed in the central European tree-ring chronologies, though overestimated in both intensity and duration of the cooling (Büntgen et al., 2015). Overall, it appears that while the effects of individual volcanic eruptions or their shorter sequences on central European droughts are difficult to isolate from the background of other influences, their existence becomes more clear from multi-century series, covering a larger number of powerful volcanic events.

The influence of AMO and PDO on drought variability has already been demonstrated in the results of several papers (e.g., Enfield et al., 2001; McCabe et al., 2004; Mohino et al, 2011; Oglesby et al., 2012). Here, a connection of Czech drought indices to both these oscillations was indicated, more prominent for PDO. This result is also consistent with the outcomes of an analysis by Mikšovský et al. (2016b), applying linear regression to the seasonal drought index data from several Czech locations in the 1883–2010 period and reporting quite a strong link to the PDO index resulting from an interaction of PDO-correlated components in both precipitation and temperature. However, a potential problem with the analysis procedure stems from the close similarity of the pair of predictors representing AMO and PDO variability. Despite the removal of the long-term temperature component from the original temperature reconstructions by Mann et al. (2009), the Pearson correlation coefficient of the two series is 0.77 over the 1501–2006 period; there is also a very strong similarity between the two signals at periods of around 20–35 years as well as around 70 years (Fig. 7). As a result, the AMO and PDO predictors are competing for the same components in the target signals and the confidence intervals of the resulting regression coefficients are inflated compared to the other explanatory variables (Fig. 4). Considering the relative similarity of magnitude and significance of the regression coefficients for AMO and PDO and their typically opposite signs, it is difficult to assign the variations in the target variables to one or the other. When employed individually (i.e. either AMO or PDO, but not both), the PDO series constitutes a more influential predictor than AMO, with links to SPEI and PDSI statistically significant at a 99% level over the 1501–2006 period. On the other hand, AMO alone produces no significant links to drought indices. To investigate this behavior further, the AMO-PDO pair was replaced with their transformation by unrotated principal component analysis. In this setup, the first principal component (PC1; representing 88% of total variance) corresponded to the arithmetic mean of the AMO and PDO series, while the second component (PC2; the remaining 12% of total variance) represented their difference. Quite surprisingly, a substantially more significant connection to the series of Czech drought indices was indicated for PC2 than for PC1. This suggests that the difference between the temperatures in the northern Atlantic and northern Pacific, rather than their common concurrent variability, is influential in the context of the interdecadal variability of central European droughts.

It should be mentioned that the fraction of variance explained by the regression mappings (R^2) is quite low in all the cases presented above: it does not exceed 0.05 for drought indices or precipitation at annual resolution in the 1501–2006 period. A slightly higher value ($R^2 = 0.14$) was achieved for the temperature series, mostly due to the match of long-term trends for temperature and of CO_2 concentration. Somewhat higher R^2 was also indicated for individual sub-periods, especially 1851–2006. Even so, the components detected in the drought indices, even when statistically significant, do not constitute a predominant source of total variability; this role appears to be played by inter-annual variations associated with weather changes closer to synoptic time scales and tied to local climate dynamics. Still, as the statistical significance of some of the links in this analysis suggests, the effects of some of the extra-European climate drivers should not be dismissed, as they appear to contribute substantially to inter-decadal variability (driven, at least partially, by temperature variations in the AMO and PDO regions) or episodic perturbations (volcanic activity).

Due to the focus on globally-acting and more slowly variable factors, the analysis herein did not consider some of the canonical drivers of more rapidly variable components in the climate system. For central Europe, these include the North Atlantic Oscillation (NAO) in particular, an oscillatory mode typically defined from the atmospheric pressure distribution over the northern Atlantic and projecting a significant influence over many aspects of the European climate, including drought variability (e.g. Brázdil et al. 2015a; Mikšovský et al. 2016b). When a NAO reconstruction by Luterbacher et al. (2002) was used as one of the explanatory variables, the link to Czech drought indices was found to be strong and statistically significant for both instrumental and pre-instrumental periods, with positive NAO phase resulting in distinctly warmer and wetter conditions, and thus negative contributions to the drought indices. In potential future extensions of drought attribution analysis, concerned with more rapid oscillatory modes in the drought data, the role of NAO (as well as its potential interactions with other drought-influencing factors) should not be ignored.

One of the key questions associated with any analysis of multi-centennial climatic signals is the issue of stability in the patterns and relations observed. While this study attempted to address this subject within its regression-based analysis, by investigating two shorter sub-periods in the data, an even finer division would prove difficult in the light of the relatively long characteristic times of some of the processes involved (such as AMO) compared to the length of the time series available. In this regard, cross-wavelet transform may provide extra insight; it appears that while periodic oscillations do not dominate Czech drought indices, some time-scales are substantially involved in the interactions between our target and explanatory variables (Fig. 7). However, none of these connections is persistent throughout the entire analysis period, even though some of them (especially the relatively coherent link indicated for periods of around 70 years) span several centuries. To better describe these links and their implications, a transition to more complex regression methods may be desirable in the future. This extension of analytical methods should also be accompanied by a more detailed analysis of the uncertainties in the pre-instrumental data, including inter-comparison with other data types (such as dendroclimatic reconstructions).

6 Conclusions

The current paper analyzed imprints of external, and some internal, climate forcings in three long-term series of drought indices (SPI, SPEI, PDSI) derived from documentary and instrumental data after AD 1501 for the Czech Lands. The results confirmed some of the previous findings derived from instrumental data; in other cases, such extended analysis period facilitated better identification and quantification of the factors responsible for Czech drought regimes, and a more complete understanding of how temperature and precipitation mediate the respective links:

(i) CO_2 concentration (and corresponding radiative forcing) matches the long-term trend component in the temperature-sensitive drought indices quite well (SPEI and PDSI, in addition to temperature itself). Even considering that statistical attribution analysis can only reveal formal similarities and cannot verify the causality of the links detected, the dynamics of the relationship during preindustrial and recent periods and other available evidence (including data from climate simulations) support the existence of an anthropogenic-induced drying effect in central Europe, primarily tied to temperature increase rather than precipitation changes.

(ii) While the results herein confirmed the lack of a solar variability imprint in the drought series, a distinct signature of temporarily wetter conditions following major stratospheric volcanic eruptions was detected, largely tied to transitory temperature decrease. This behavior appears undetectable from instrumental data alone, probably due to the insufficient number of large volcanic events.

(iii) Unlike the mostly non-significant response to ENSO, both AMO and PDO appear to be tied to decadal and multidecadal components in (at least some) drought indices. Even more curiously, a more significant drought component appears to be tied to the difference between AMO and PDO values rather than to their common component. Further validation will be, however, needed to verify whether this behavior is a manifestation of actual physical links, or a feature associated only with the specific AMO and PDO reconstructions used.

Finally, the results herein also indicated some potentially prominent, but not completely stable relations between the time-series investigated. In the future, these should be investigated more closely, as a better understanding of them is vital to proper analysis of records spanning many centuries. In this context, the reliability of the reconstructed records needs to be addressed in more detail. Transition to more complex statistical techniques (possibly nonlinear) may also be desirable, although challenges will have to be overcome related to higher uncertainty and the sometimes limited information content of document- and proxy-based data.

Data availability

The series of explanatory variables for external climate forcings, as well as internal climate variability modes, were obtained from the KNMI Climate Explorer database – https://climexp.knmi.nl. The central European temperature series is available on https://www.ncdc.noaa.gov/paleo-search/study/9970, while Czech precipitation and drought indices series are available from the authors.

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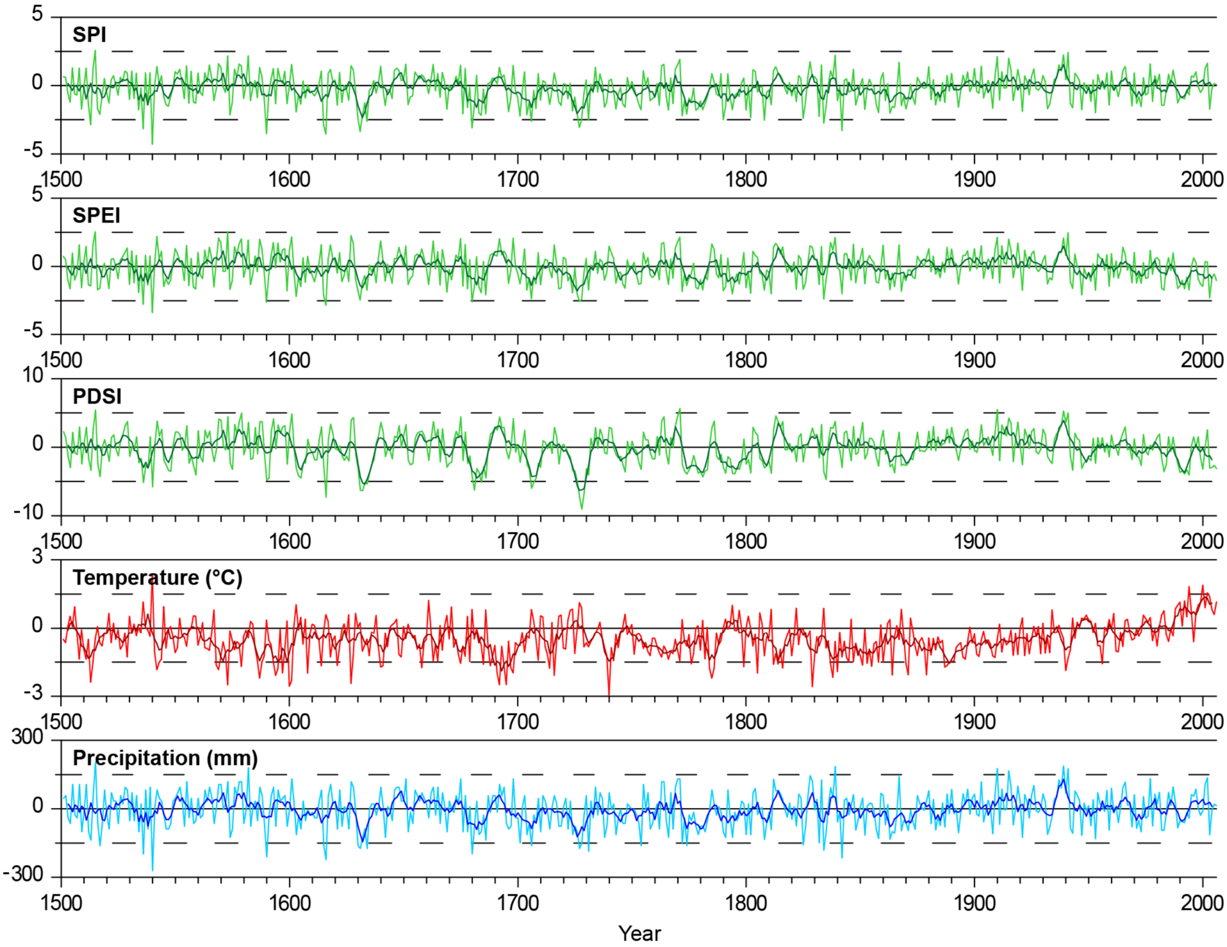

Figure 1. Fluctuations in annual drought indices, temperature and precipitation anomalies (w.r.t. 1961–1990 reference period) for the Czech Lands in the AD 1501–2006 period; smoothed by 11-year running means (darker lines).

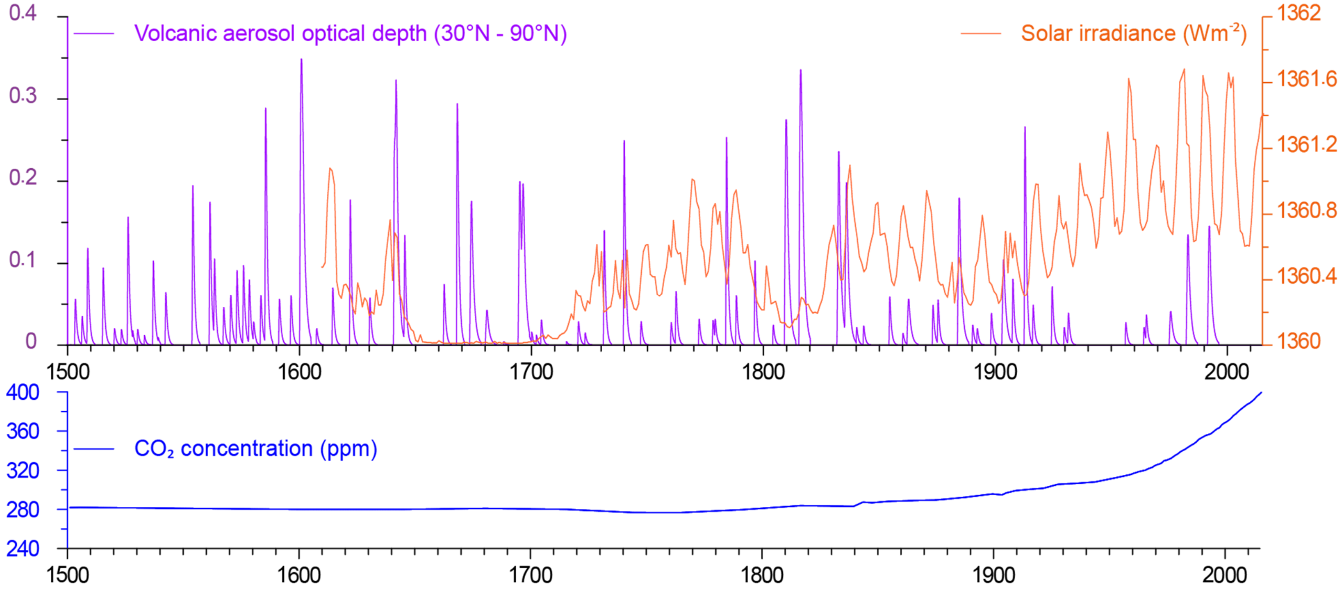

Figure 2. Fluctuations in the annual series of external forcing descriptors (volcanic aerosol optical depth for 30°N–90°N, solar irradiance and CO_2 concentration).

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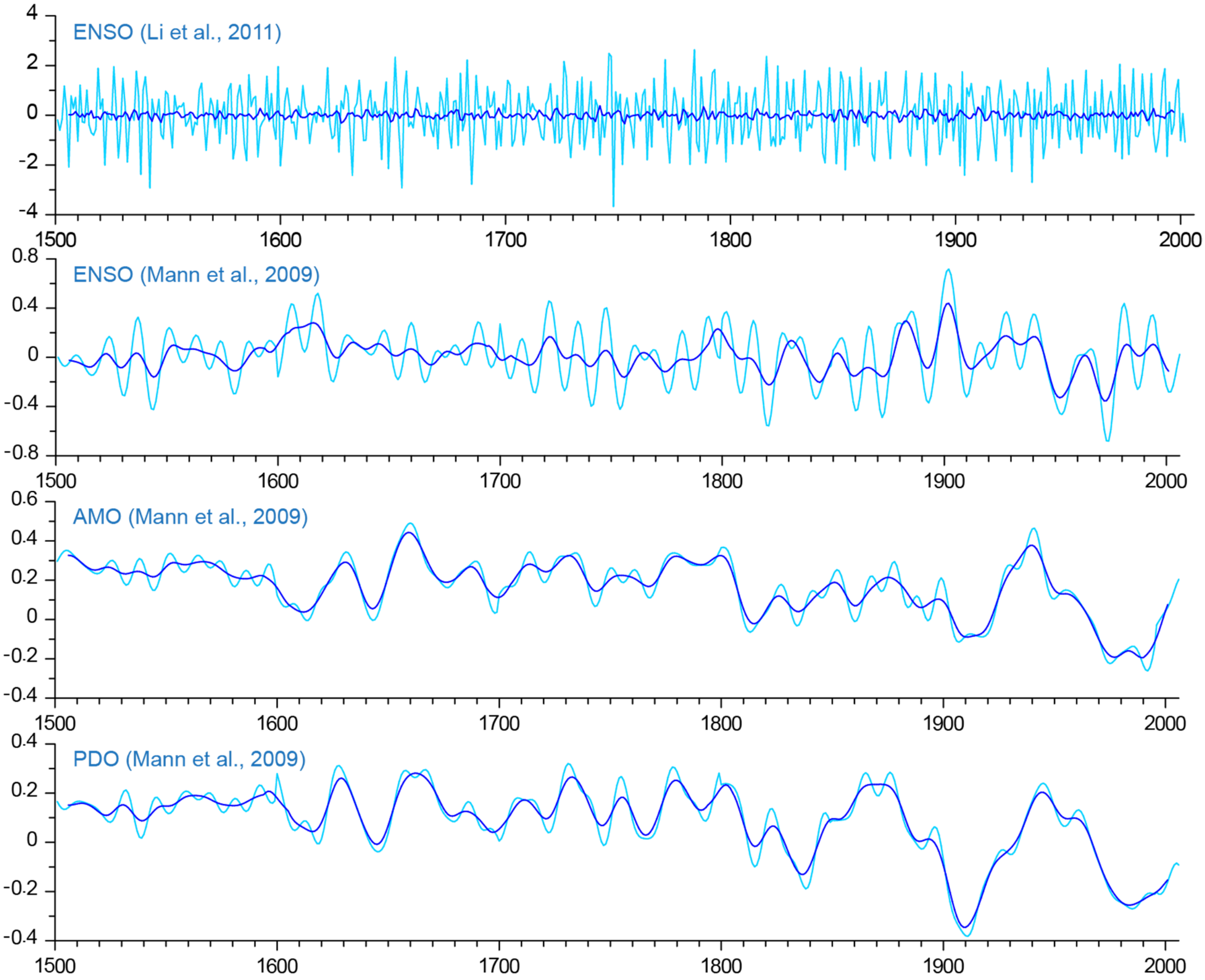

Figure 3. Fluctuations in annual series of internal climate variability modes (ENSO index by Li et al. (2011); ENSO, AMO and PDO indices derived from data by Mann et al. (2009), detrended by 70-year running mean of northern hemispheric temperatures); smoothed by 11-year running means (darker lines).

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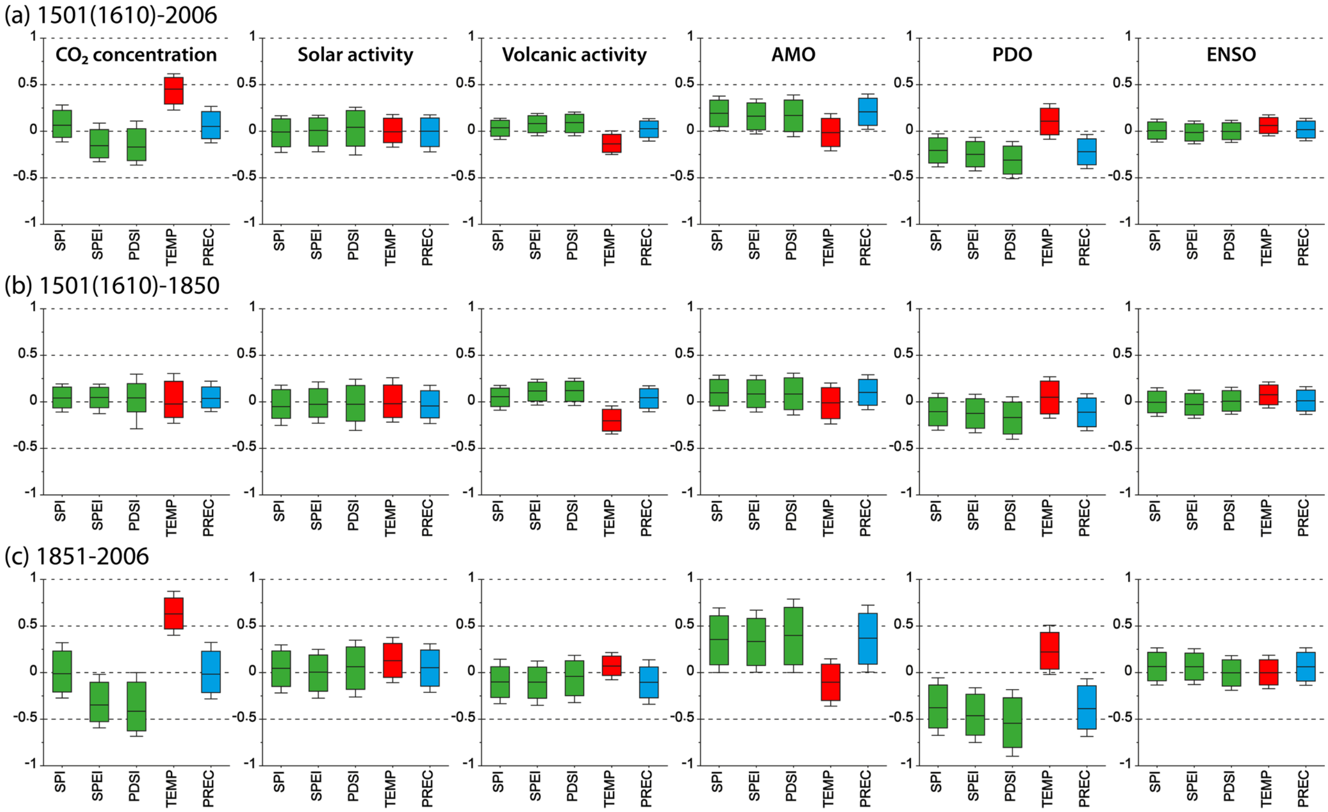


Figure 4. Standardized regression coefficients (central line, with 95% confidence interval shown as the box and 99% confidence interval as the whiskers), obtained by multiple linear regression between the predictands characterizing local Czech climate (drought indices – green, temperature – red, precipitation – blue) and a set of explanatory variables representing external forcings and large-scale internal climate variability modes in various periods: a) 1501(1610)–2006, b) 1501(1610)–1850, c) 1851–2006.

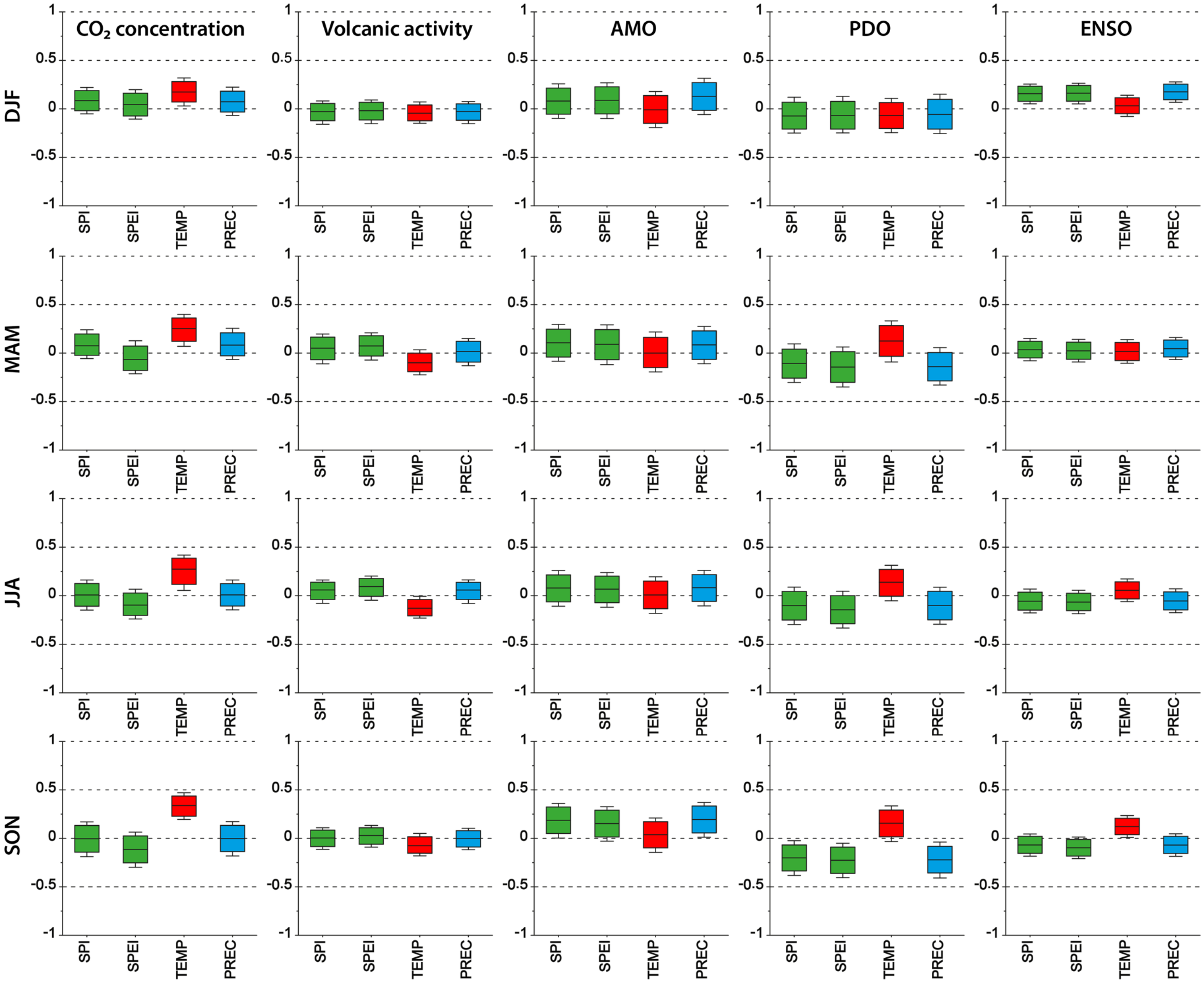


Figure 5. Standardized regression coefficients (central line, with 95% confidence interval shown as the box and 99% confidence interval as the whiskers), obtained by multiple linear regression between the predictands characterizing local Czech climate (drought indices – green, temperature – red, precipitation – blue) and a set of explanatory variables representing external forcings and large-scale internal climate variability modes; period 1501–2006, individual seasons.

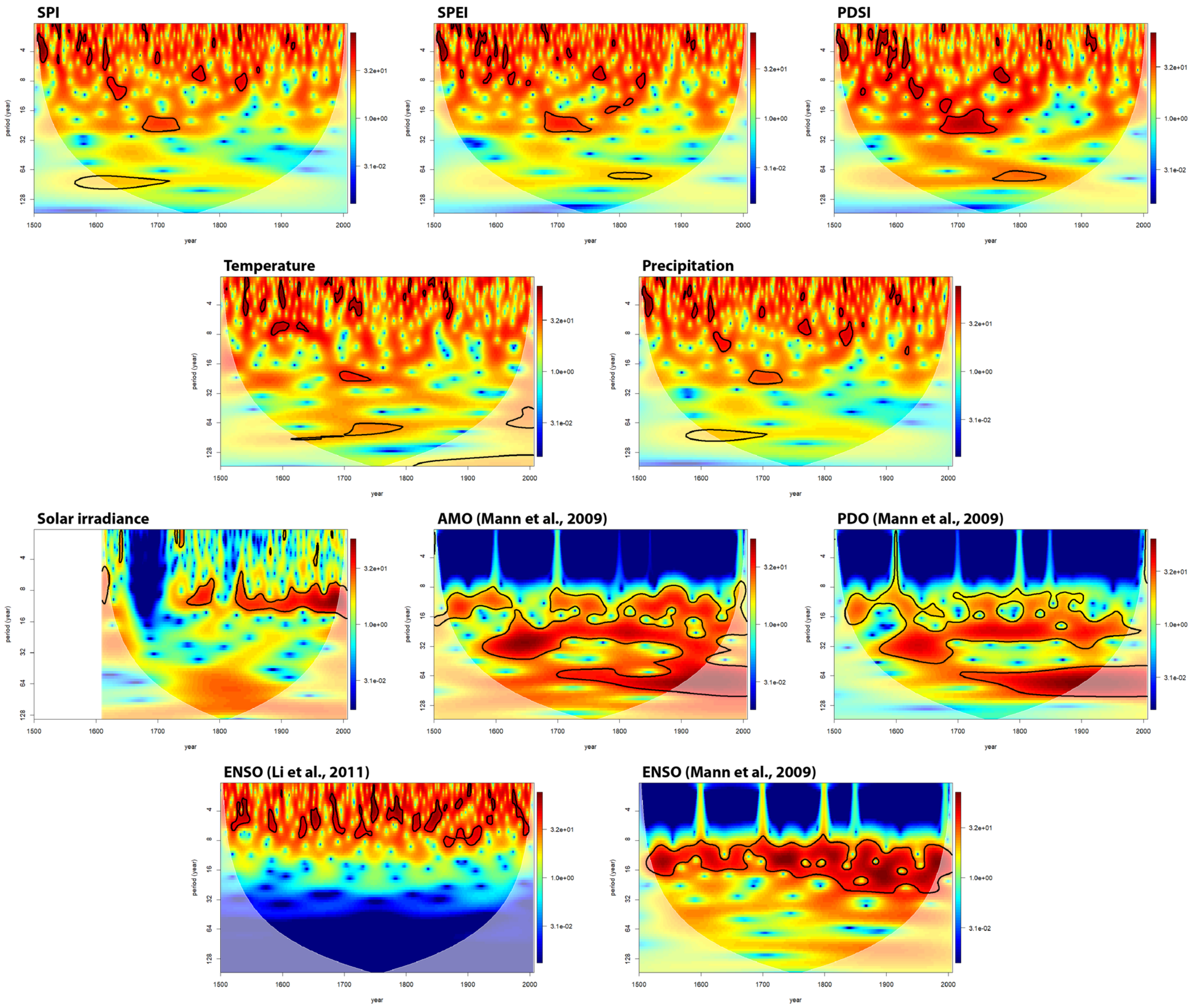
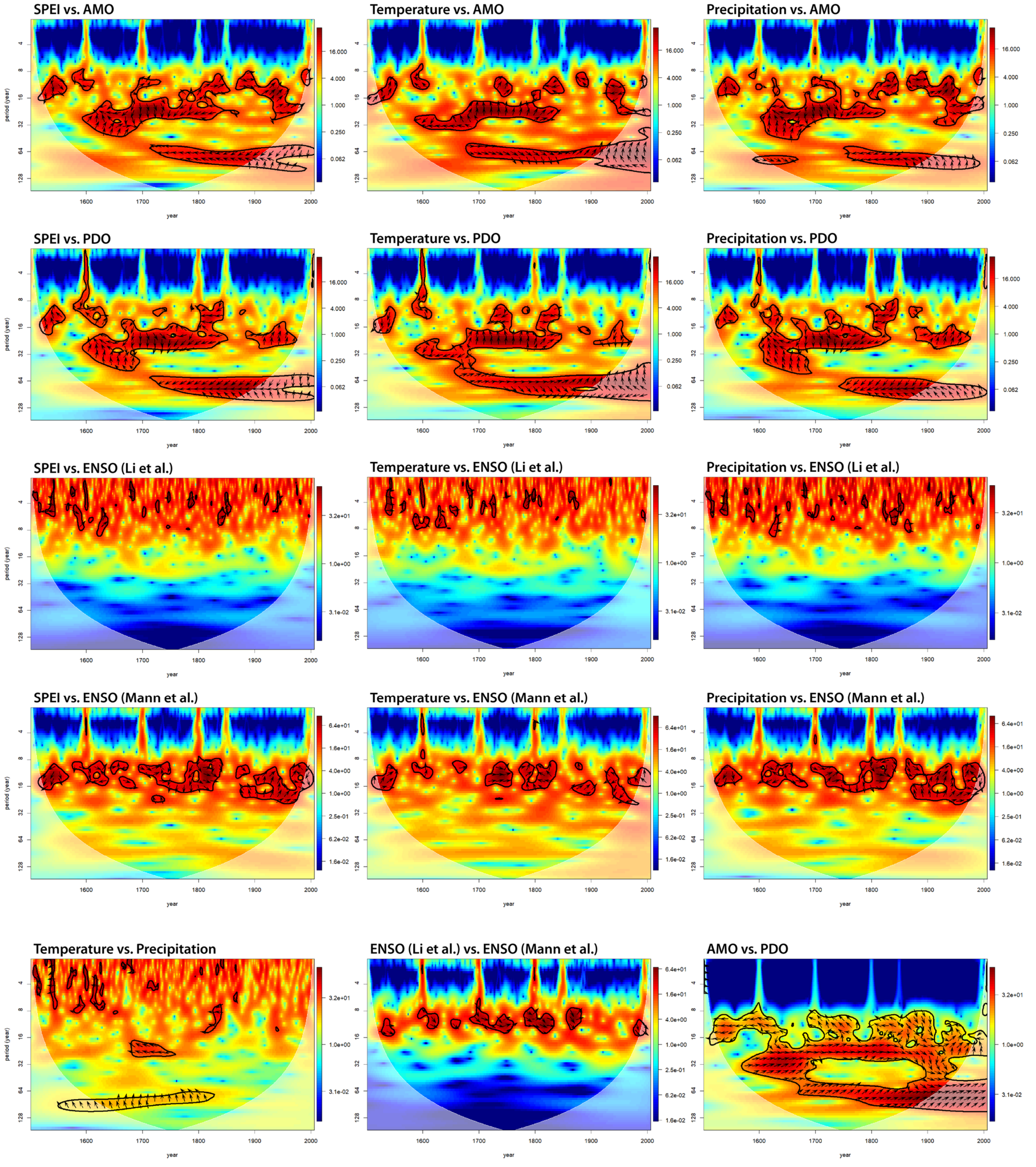


Figure 6. Wavelet power spectra of annual series of Czech drought indices, temperature, precipitation, and selected explanatory variables (continuous wavelet transform, Morlet). Areas enclosed by black line correspond to wavelet coefficients significant at the 95% level, AR1 process null hypothesis.



SPEI vs. AMO

Temperature vs. AMO

Precipitation vs. AMO

SPEI vs. PDO

Temperature vs. PDO

Precipitation vs. PDO

SPEI vs. ENSO (Li et al.)

Temperature vs. ENSO (Li et al.)

Precipitation vs. ENSO (Li et al.)

SPEI vs. ENSO (Mann et al.)

Temperature vs. ENSO (Mann et al.)

Precipitation vs. ENSO (Mann et al.)

Temperature vs. Precipitation

ENSO (Li et al.) vs. ENSO (Mann et al.)

AMO vs. PDO

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Figure 7. Standardized cross-wavelet spectra between series of Czech SPEI, central European temperature, Czech precipitation and selected explanatory variables with distinct oscillatory component (annual time-step; standardized and bias corrected, as per Veleda et al., 2012). Coherences statistically significant at the 95% level are enclosed by black line; the arrows indicate local phase difference, with → corresponding to the two signals being in phase and ← indicating a shift of half the period.