We would like to thank all three anonymous referees for their valuable comments regarding our manuscript. We tried to incorporate the corresponding modifications into our analysis and its proposed presentation in the revised paper, or bring arguments in cases when we were unsure how the proposals could be implemented into the manuscript without too severe changes of its context or aim.

Main changes to the analysis and its presentation in the revised manuscript:

- Results involving effect of the North Atlantic Oscillation (NAO) have been added in a quantitative form (whereas in the original manuscript, only a brief mention of NAO effects was made in text).
- More reconstructions have been employed to represent the AMO index (2 versions in total) and PDO index (3 versions in total) and comparison with the previous results based just on the reconstruction by Mann et al. (2009) has been provided. Predictor representing radiative forcing due to changes in the atmospheric composition has been altered to involve the aggregate effect of multiple greenhouse gases rather than just carbon dioxide. The solar variability predictor has been replaced by the recently published Total Solar Irradiance (TSI) data by Lean (2018), covering the entire 1501-2006 period, whereas the data by Coddington et al. (2016) are now used as an alternative solar activity descriptor.
- Discussion of the results has been expanded to pay more attention to the potential interactions between individual predictors.
- Additional results have been added to better illustrate properties of the regression mappings, including values of the coefficient of determination, samples of regression-estimated components associated with individual predictors, and graphs of regression residuals and their autocorrelation functions.
- Electronic Supplement has been added to the manuscript to hold extra materials illustrating outcomes of the supporting analyses.

Please see below for specific responses to the comments of referees 1, 2 and 3 (R1, R2, R3) and description of the corresponding changes to the manuscript.

The marked-up version of the manuscript, detailing the changes made, is attached at the end of this document.

Anonymous Referee #1

The paper analyses the long-term variability of droughts in the Czech lands based on long reconstructions (based on instrumental and documentary data). Time series of drought indices, temperature and precipitation are compared to reconstructions or time series of suspected drivers such as external forcings and oceanic variability modes. Anthropogenic radiative forcing as well as AMO/PDO are identified as influencing factors. The paper is interesting, valuable to the community and within the scope of Climate of the Past. However, I have several comments, which I think the authors should consider, before the paper can be published.

Methods

It is not fully clear which data are monthly or seasonal. Often the text mentions "seasonal and annual" or "monthly, seasonal and annual", which I found confusing. Also, the drought indices are usually calculated for individual measurement locations or grid cells. Here they are calculated for a large-scale average, as I understand. This should be made clear and explained. In the results section it then becomes clear that the seasons are analysed separately. However, what is the motivation for analysing a autumn or winter drought index?

> **Response R1-1:** The data description (Sect. 2.1, 2nd paragraph) should now make it more clear that the analysis was carried out on either series of true annual values (i.e., consecutive values representing means for an entire year) or series of season-specific means (i.e., one seasonal value for each year). The note regarding monthly series in Sect. 2 pertains to some of the original data sources; monthly values were not directly studied in the current analysis. The nature of the drought indices as area-wide means is now more explicitly stated in the text (Sect. 2.1, 1st paragraph). Since drought data for all seasons (including autumn and winter) were available and analyzed, we present the outcomes for all four seasons, to illustrate the full range of potential climate links. It should also be considered that even though for some applications (such as investigation of agricultural droughts) spring and summer conditions may be of greater interest, recharge of the underground water resources and surface reservoirs depends on the water available during autumn and winter and droughts in these periods often induce major hydrological impacts in the following year.

Multiple linear regression is used to separate individual components, but fully separating external forcing from internal variability (e.g., oceanic modes) is fundamentally difficult. External forcings might operate via altering internal variability modes (e.g. solar and volcanic forcing might change the climate system via AMO or ENSO). Conversely, AMO and PDO have the imprint of global temperature rise. I see that the authors use cross-wavelet spectra, partly to assess the interdependencies, but not systematically. Partial correlation methods could be used to go into more depth here, or different models could be compared. In any case, the interpretations should be phrased very carefully.

> **Response R1-2:** Indeed, the problem of separating the strictly external forcings from the internally induced variability is a complicated one, not only at a statistical level, but also with

regard to the underlying physical mechanisms. While this was not mentioned in the manuscript, we examined the mutual links between individual predictors with episodic or oscillatory components in terms of Pearson (cross-)correlation. Although some potentially noteworthy correlations appeared, none of them (other than the AMO-PDO relation) seemed strong and stable enough to warrant a specific treatment of inter-predictor links, at least not in the context of purely linear regression. Therefore, in our analysis eventual external forcing-induced components in the indices of internal climate variability modes were treated as a part of these indices; components attributed by the regression analysis to the forcings themselves were then treated as direct responses. To provide a more complete picture of the potential indirect effects of external forcings manifesting through their influence on the internal climate variability modes, results of analysis carried out with just the predictors representing external forcings (solar, volcanic, anthropogenic) have been added to the revised manuscript (Fig. S1a in the Supplement), and they are mentioned in the main text (p. 16, l. 18+). The effect of solar and volcanic forcing on NAO is also discussed (paragraph starting at p. 16, l. 3) and documented in the Supplement (Fig. S7). Furthermore, the Discussion has been expanded to provide additional references to some works addressing the influence of external forcings on NAO (Ortega et al., 2015; Sjolte et al., 2018). We did, however, not attempt to extend our analysis to involve the effects of external forcings on long-term components in the internal climate variability modes (particularly AMO and PDO), as this issue would require a considerably different methodological approach.

In the case of the imprints of global temperature in the AMO and PDO indices derived from data by Mann et al. (2009), please note that the long-term temperature component (in the form of mean northern hemispheric temperature) has been removed from the data during pre-processing (as described in Sect. 2.2), and the AMO/PDO predictors therefore only encompass oscillatory variations around the hemispheric temperature series. This is stated in the respective paragraphs of Sect. 2.2.

Due to the sheer amount of possible combinations, results of the cross-wavelet analysis were only presented for selected pairs of predictors/predictands, either those showing interesting interactions, or those intended to illustrate a similarity or contrast in behavior compared to some other pair of variables. In the revised version, the interactions between SPEI, temperature and precipitation and the primary predictors have been retained in the manuscript (Fig. 7); results for the alternative predictors are given in the Supplement (Fig. S2). Selected additional cross-wavelet spectra have also been added to the Supplement, illustrating interactions between predictands (Fig. S3a) and between different predictors and their versions (Figs. S3b, S3c).

While we agree that partial correlations can offer additional insight into the interdependencies in a multivariable system, their use does not necessarily solve the ambiguity arising from the existence of a common, physically relevant component within multiple explanatory variables, stemming not from a one-way causality, but rather from a two-or-more-way interaction. Such a component cannot be reliably assigned by purely statistical means and since its origin is typically rather complex, we prefer to deal with its presence and interpretation during the discussion of the results. Note also that in the most prominent case of such collinearity in our analysis, related to the similarity between AMO/PDO predictors by Mann et al.

> (2009), we addressed this problem by carrying out regression with mean value and difference of the AMO and PDO series; the outcomes are now shown explicitly (Fig. S1c) rather than just mentioned in the main text. Results for regression involving AMO-only and PDO-only configuration of predictors are now also included (Fig. S1b) instead of just discussed.

The regression model itself is not explained clearly. From the text it becomes clear that different ENSO indices were used, but which model (which ENSO index) is the one shown in Figs. 4 and 5? Furthermore, only very late in the paper we learn that the explained variances are very low, below 5%. Should we even analyse regression models that have no explanatory power? Finally, the effect of reconstruction uncertainty is not discussed.

> **Response R1-3:** The missing identification of the primary ENSO index has been corrected – it is now explicitly stated that the results in Figs. 4 and 5 are based on the ENSO reconstruction by Li et al. (2011). Furthermore, due to the inclusion of alternative predictors in the revised version of the manuscript, individual data sources are now systematically specified in the individual figures whenever more than one version of the predictor exists.
>
> The seemingly low fraction of variance explained by the regression models (R^2) is a result of dominance of inter-annual variability in the predictand series, matched in the regression mapping against predictors mostly dominated by inter-decadal variation. Formally, higher R^2 could be achieved by removing the year-to-year variations, e.g. by smoothing the series by a moving average filter (to give an example, for the period 1501-2006, 21% of variability of the annual SPEI series can be explained by the regression model if the series are smoothed by 11-year moving average; this value increases to 33% when the NAO reconstruction by Luterbacher et al. (2002) is also included as a predictor). However, since some of our explanatory factors (the episodic volcanic activity, 11-year cycle in the solar variability signal, and the NAO index in the revised version of the analysis) do exhibit faster variability, which would be largely erased by the smoothing, we prefer to perform the analysis with the unaltered series. The prominence of individual explanatory factors is evaluated through statistical significance of the respective regression coefficients, regardless of the overall R^2 – an approach that we believe to be consistent with our primary aim, i.e. identification of forcings and large-scale factors influential in establishing the drought regime of the Czech Lands (as opposed to an attempt to construct a predictive model reproducing the series with as much variability as possible). To better illustrate the actual magnitude of components associated with individual explanatory factors, a sample of time series of regression-generated components corresponding to individual explanatory variables has been included in the Supplement (Fig. S5); furthermore, values of R^2 have been added to Figs. 4 and 5 for each of the regression configurations.
>
> The effect of uncertainties tied to the results would be rather difficult to quantify reliably, as not all series analyzed come with an uncertainty estimate, and methods of its estimation differ even when such data exist. However, due to increased number of versions of some predictors in the revised version of the analysis, more attention is paid in the revised manuscript to the robustness of the results based on different reconstruction sources.

The paper says little about the mechanisms linking the external and internal drivers to drought and hydroclimatic conditions in general. Obviously a study using reconstructions cannot explicitly address net radiation, soil moisture, temperature effects, land-surface feedbacks, atmospheric circulation effects (blocking), etc. But it would be nice to read the authors' hypotheses. The paper is rather silent about mechanisms. In the introduction Hess-Brezowsky weather types are mentioned, and later the NAO, but the NAO is not incorporated into the analyses and the discussion parts then follows another thread: Doing a PC analysis of AMO/PDO. It would be nice if the Discussion section could come back to mechanisms at some point.

> **Response R1-4:** Note please that our study is dealing with droughts defined through the SPI/SPEI/PDSI indices, shaped by (and calculated from) precipitation and temperature series. Our interpretation of the possible links is therefore focused on the role and eventual interaction of the temperature and precipitation variability in establishing the central European drought regime expressed by the above indices. Also note that some of the responses, while statistically significant, represent rather minor tendencies, difficult to reliably assign to specific mechanisms (especially in our analysis involving pre-instrumental period, as no data exist consistently capturing global large-scale circulation over the last five centuries, making it difficult to evaluate influences related to circulation, blocking, etc.).
>
> NAO-related effects have been included in the revised version of the manuscript, based on the NAO index reconstructions by Luterbacher et al. (2002) and Ortega et al. (2015) as well as multidecadal NAO variability reconstruction by Trouet et al. (2009). The results in Figs. 4 and 5 have been updated to show regression coefficients related to NAO in addition to the previously considered predictors; the Discussion has been expanded to include analysis of the NAO-related links.

Minor comments

Abstract, l. 14: "external and internal climate forcings". Please be careful with terminology here and elsewhere. Considering the coupled climate system "forcing" is used for external influences (subdivided into natural and anthropogenic) while internal variability is used for the dynamics of the coupled system even if unforced. When considering only the atmosphere, "oceanic forcing" is sometimes used. In any case, the terms should be defined and used consistently.

> **Response R1-5:** Terminology in the manuscript has been modified to avoid use of the term 'forcing' for factors originating from internal climate dynamics.

P. 2, L. 5: a substantial number of studies: cite
P. 2, L. 5: A lot of work has been done on droughts in the USA. Perhaps before zooming in on Europe, you could mention that.

> **Response R1-6:** Both comments accepted, corrected by adding new references as follows (p. 2, l. 15 in the revised manuscript): "In addition to a substantial number of studies investigating drought indices for the instrumental period in Europe (e.g. van der Schrier et al., 2007, 2013;

Briffa et al., 2009; Sousa et al., 2011; Todd et al., 2013; Spinoni et al., 2015; Haslinger and Blöschl, 2017) and other areas of the world (e.g. Dai, 2011; Spinoni et al., 2014; Ryne and Forest, 2016; Wilhite and Pulwarty, 2018), generally calculated …".

P. 2, L. 24: instrumental precipitation series

Response R1-7: Corrected as "The authors demonstrated the importance …"

P. 3, L. 10: What time window was used for the SPI?

Response R1-8: The time window used for the SPI/SPEI calculation was chosen to match the type of the series used as predictand, i.e. 12 months for the annual data, 3 months for seasonal data.

P. 4, L. 3 and 4: I do not understand this sentence.

Response R1-9: The sentence has been changed to (p. 4. l. 26): 'As a result, a 100-member ensemble of distributions of monthly precipitation totals for each season and the year was obtained. These distributions were then applied for calculation of indices for every year in the 1501–1803 period.'. Note, please, that this is just a substantially simplified description of the data preparation process, and full explanation can be found in Brázdil et al. (2016a).

P. 4, L. 10: "climate forming agents": rephrase

Response R1-10: Reformulated to 'climate-defining factors'

P. 4, L. 19 and 20: Omit the first part of the sentence, which is unnecessary. Start with "A large part..."

Response R1-11: Accepted

P. 4, L. 26: strong clear?

Response R1-12: Changed to 'clear'

P. 5, L. 1-3: Perhaps cite Fischer et al. GRL (https://doi.org/10.1029/2006GL027992)

Response R1-13: The reference to Fisher et al. (2007; DOI 10.1029/2006GL027992) has been added to the revised manuscript.

P. 5, L. 19: I am a bit puzzled why the authors use the Mann et al. ENSO series. As the authors write (and other authors have also pointed to that), the reconstruction varies mostly on the 8-20 year time scale. Why use it as an ENSO time series then? I would rather use other ENSO reconstructions. Similarly, for AMO and PDO it would be nice to have two indices for each (e.g. Shen et al. 2006 for the PDO, Gray et al. 2004 for the AMO).

Response R1-14: Please note that ENSO reconstruction by Li et al. (2011) was used as the primary descriptor of ENSO, and a basis for the results shown in Figs. 4 and 5. ENSO index derived from the Mann et al. (2009) data was only used as an alternative ENSO descriptor. This should now be more clear from the revised text, as more thorough identification of individual data sources is given throughout the text. Regression outcomes for Mann et al. (2009) ENSO data are now included in the Supplement (Fig. S1i).

Results based on the PDO reconstructions by MacDonald and Case (2005) and Shen et al. (2006) and AMO reconstruction by Gray et al. (2004) have been included in the revised manuscript and discussed along with the outcomes of the analysis utilizing the originally employed PDO/AMO data by Mann et al. (2009). Regression coefficients are presented for each version of the predictors (some of them in the Supplement, Fig. S1); their similarity (or lack thereof, as is the case for the PDO reconstructions) is now discussed with regard to the robustness of the results and the associated uncertainties (in the relevant sections of the Discussion).

P. 10, L. 34: Is the tendency for wet conditions after volcanic eruption really due to lower temperatures?

Response R1-15: This formulation is meant to reflect the fact that the tendency towards higher values of the drought indices during periods with higher amounts of volcanic aerosol coincides with significant drop of temperature, while no statistically significant change in precipitation is indicated.

P. 11, L. 34: I am surprised that Sutton and Hodson (2005) paper is not mentioned in context with the AMO effect.

Response R1-16: The reference to Sutton and Hodson (2005) has been added to the revised manuscript (p. 13, l. 31).

Anonymous Referee #2

GENERAL COMMMENTS:

Manuscript under revision is an approach to study of drought in Czech Republic area, taking in consideration previous climatic reconstructions, already published, using these informations to generate drought indices based on instrumental records. Analysis of possible relations with different forcing factors is also made to offer general or initial explanation to drougth mechanisms for this Central Europe study area.

Main effort focused to compare rainfall indices and temperatures for long or complete periods. It's a good first approach to drougth phenomena. It open research to study specific events at higher temporal resolution, impacts and responses, etc.

SPECIFIC COMMENTS

+ Title could include temporal dimension of work of manuscript.

> **Response R2-1:** Because we are using the expression "long-term", it is probably not necessary to extend the title for the time span used.

+ Title. Expression "drought" into title is excessively general. A more correct definition of topic developped into manuscript would be "drought indices".

> **Response R2-2:** Accepted and also with respect to a comment of Referee 3 changed to "Long-term variability of drought indices in the Czech Lands and effects of external forcings and large-scale climate variability modes"

+ Lines 28-30. Seasonal and annual precipitation for 1501-1854 is reconstructed from "document-based precipitation indices". Dobrovolvy et al., 2015. Could explain in a short description general characteristics or contents of these "documents"? How was developed previous analysis. Just to have a connection between original information and present results generated into manuscript. IF drought is analyzed, at least public must know about historical documents used for reconstruction, temporal resolution of information obtained, locations or regions with available information, aspects of natural process and/or and human impacts detected/evaluated....etc.... I understand manuscript can have restrictions of extension, but this short overview would be useful for public.

> **Response R2-3:** This comment and several following remarks of Referee 2 concern details related to the documentary data used. We would like to stress that the primary aim of the analysis is the study of forcings and large-scale climate drivers reflected in series of drought indices, described in detail in the paper by Brázdil et al. (2016a). Because their calculations are based on reconstructed temperature (Dobrovolný et al., 2010) and precipitation (Dobrovolný et al., 2015) series, in which a detailed information of documentary data used with their types, examples and critical evaluation are given (as well as the reconstruction uncertainties), it would

bring not too much new information to the merit of this article. But looking at the comments of the Referee 2, we included several additional sentences in this direction with hope to fulfill at least partly these requests by the change of the fifth paragraph of Section 2.1 as follows (p. 4, l. 3):

"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. Documentary data comprised descriptions of weather and related phenomena from a variety of documentary evidence, some of it individual, some of it of an institutional character, such as annals, chronicles and memoirs, weather diaries (non-instrumental observations), financial and economic accounts, religious records, newspaper and journals, epigraphic sources, and more. Such data in the Czech Lands cover particularly, at varying degrees of density, the period from AD 1501 to the mid-19th century, but continue even to the present time. The spatial density of such data changes over time, depending on the availability and extraction of existing documentary sources. All the data collected were critically evaluated with respect to possible errors in dating or spatial attribution and were used for interpretation of monthly-weighted temperature and precipitation indices on a 7-degree scale, from which series of seasonal and annual indices were created (for more details of the use of documentary data, its critics, analysis and interpretation, as well as creation of series of indices in historical climatology, see Brázdil et al., 2005, 2010). Such data were further used as a basic tool for temperature/precipitation reconstructions. 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 documentary-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)."

+ Bibliography used on work is complete and well updated.

Response R2-4: Thank you.

+ Effort to offer a background or general overview about drought events is not so complete as we would like find. For example, justification of study of drought. It's a present or potential problem for Czech Republic?, any previous strong event justify this study? How they are drougth conditions in Czech Republic?

Response R2-5: To fulfill this comment, the first paragraph of Introduction has been changed as follows: "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). This is also valid for the territory of the Czech Republic where droughts, apart from floods, constitute the most important natural disasters, with significant impacts upon various sectors of the national economy, such as agriculture, forestry, water management, and tourism/recreation. Since the Czech Republic lies on a continental divide with rivers flowing out of its territory, it depends on atmospheric precipitation alone for its water supply. Although certain extreme droughts with important socio-economic and political impacts are known from the past, such as the drought of 1947 (Brázdil et al., 2016b), studies performed in recent years show the Czech climate has become increasingly dry in the past 2–3 decades, expressed in terms of higher frequency of extreme droughts with significant consequences (e.g. Brázdil et al., 2015b; Zahradníček et al., 2015). The abundance of long-term instrumental meteorological observations 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, in the European area (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) as well as other areas of the world (e.g. Dai, 2011; Spinoni et al., 2014; Ryne and Forest, 2016; Wilhite and Pulwarty, 2018). 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). "

+ Historial dimension of drought is not analyzed. Just index values from previous research considered as approach to climatic patterns related to low values of reconstructed precipitation. Drought is not studied by itself as climatic/historic phenomena. This aspect is not negative nor positive. Just it would require any extension of explanations about drougth as climatic pehnomena in introduction of work.

> **Response R2-6:** As explained above, our manuscript concentrates on the explanation of effects of external forcings and large-scale climate drivers on long-term drought indices variability in the Czech Lands. This means that we are really not analyzing "historial dimension of drought" as the referee correctly states because it does not fit to the concept of this paper.

+ No specific drought events are mentioned. No description at least for one event is included into manuscript. Complexity of drought events and related impacts is not described/evaluated. May be authors are preparing other papers with these specific topics?

> **Response R2-7:** The description of any "specific drought event" does not fit to the paper context, analyzing rather effects of external forcings and large-scale climate drivers in long-term drought indices series. Descriptions of specific drought events in the Czech Lands can be found, for example, in Brázdil et al. (2013) or Brázdil et al. (2015b). Moreover, the paper "Extreme droughts and human responses to them: the Czech Lands in the pre-instrumental period" by Brázdil et al. was currently submitted to Climate of the Past (https://doi.org/10.5194/cp-2018-135).

+ No explanation about drought as climatic phenomena. How is considered drought in Czech Republic, what criteria are applied, what instrumental thresholds, duration/extension/severity, different concepts/definitions of drougth, affectation of agriculture.... Any explanation would be useful to understand characteristics and effects for public unknowning these specific details.

> **Response R2-8:** We would like to stress that we are not concentrating in this paper primarily on "drought as climatic phenomena" or "what criteria are applied, what instrumental thresholds, duration/extension/severity, different concepts/definitions of drought, affectation of agriculture", because it was analysed already in many other papers related to the territory of the Czech Republic (for comprehensive overview see e.g. Brázdil et al., 2015b). We are just trying to find how fluctuations in series of drought indices in the Czech Lands are influenced by external forcings or large-scale climate drivers.

+ If drougth is defined only from specific indices (SPI, SPEI...), when we work in historical time, out of instrumental data availability, this topic must be taken with more introductory explanations. A more complete and informative approach about how documentary records detect and define droughts, what they record, what transmit....

> **Response R2-9:** We would like to stress that drought indices are not primarily derived (calculated) from documentary data, but from temperature/precipitation reconstructions based on documentary-based indices series and overlapping instrumental series. For this reason we are of the opinion that comment "A more complete and informative approach about how documentary records detect and define droughts, what they record, what transmit...." could be difficult to follow in the recent concept of our paper.

+ If manuscript is based on previous reconstructions, focused on reconstructed values of mm. rainfall, by total monthly/seasonal/annual resolution, authors must consider they cannot analyze all dimension of droughts. Rainfall indices with positive aspect can cover important drought events, when dry periods are interrupted by strong rainfall events. Knowing what tipe of drougth is under study, these singular aspects could be differenced, generating a better and deeper study.

> **Response R2-10:** We agree with the opinion of referee 2 but we are not analyzing drought on the base of precipitation indices. Precipitation reconstruction was used only as one of two basic series which were used to calculate series of drought indices.

+ Manuscript doesn't show a clear relation of type of documents and type of information rescued and anallyzed.

> **Response R2-11:** As mentioned in Section 2.1, we analyse effects of external forcings and large-scale climate drivers in long-term variability of drought indices series, calculated from reconstructed series of temperatures (Dobrovolný et al., 2010) and precipitation (Dobrovolný et al., 2015). Both these papers contain detailed information about types of documents and information rescued and analysed. Calculation of drought indices was explained in detail in the

paper by Brázdil et al. (2016a). From these reasons we do not see as necessary to repeat in detail all these aspects in the present paper.

+ It would be interesting focuse efforts on variability and extreme events of the same variable before to compare with variability of others proxys.

Response R2-12: Aspects reported by the referee (variability, extreme events, …) were dealt in a great detail already in the paper by Brázdil et al. (2016a). We feel it redundant to repeat it here again because it does not fit to the context of the present article.

Anonymous Referee #3

Description

This paper addresses the understanding of the variability of droughts, temperature and precipitation in the Czech lands 1500-present from the point of view of its dependence on internal drivers (e.g. some specific modes of circulation) and also external forcing factors (volcanic, CO2, etc). For that purpose a multiple linear regression is applied having as predictand variables 3 drought indices and as predictors a set of external and internal drivers.

The purpose of the paper has value and meaningful and solid results in this direction would be worth to be published in CP. If attribution of drought variability or a meaningful step forward in its understanding in the Czech Lands would be attained I think this would be sufficiently valuable in my view to support publication. Therefore, I encourage authors to pursue this line of work towards publication. At this state, I would recommend major revision of the manuscript. There are several issues related to the rationale, methodology and description and interpretation of results that in my understanding require revision. I will argue about this in the following points.

General Comments

GC1 General approach to attribution As it is described in the paper, 5 predictand series (3 drought indices and a temperature and a precipitation series) are examined using multiple linear regression as functions of independent predictors, the latter being internal and external in nature. In practice, these are 5 individual multiple regressions.

Having that in mind I would suggest to consider the analysis, description and discussion of the: a) selected predictors; b) of the methodological approach; and c) of the residuals of the methodology.

a) Selected predictors. I would argue these are insufficient in both the case of the external and internal subsets.

a.1-Regarding external predictors I have no objections to the ones considered so far but the authors should discuss why important predictors like other greenhouse gases (GHGs), aerosols and particularly land use land cover (LULC) are not considered. For the case of other GHGs than CO2, it would be more elegant either to consider them or to use equivalent CO2. For the case of aerosols some arguments or strategy or implementation should be considered also. For the case of LULC, this would really be an important variable since it can have an impact on drought. If any significant trends are found, how can we attribute them arbitrarily to CO2 or to a mix of the influence of GHGs and aerosols? If there has been progressive changes in LULC in the area, in the context of this manuscript, eluding them would be really misleading for the results of this analysis.

> **Response R3-1:** It is true that using just CO_2 concentration as an approximation of anthropogenic influence oversimplifies the setup. In the revised version of the analysis, aggregate radiative forcing of multiple GHGs (including CO_2, CH_4 and N_2O) is therefore used instead. As for the inclusion of the effects of (tropospheric) aerosols, their regional effect is difficult to consider in

an analysis such as ours, due to high temporal and spatial variability of their concentrations and differences in behavior of different aerosol species. Note also that from a standpoint of a regression analysis, the predictors with and without the aerosol forcing are usually quite similar, as the respective time series are very strongly correlated. For instance, using the Meinshausen et al. (2011) global annual concentration and forcing data over the 1765-2005 period, the CO_2 concentration series is correlated with total anthropogenic forcing (representing the aggregated effect of various greenhouse gases as well as aerosols) at 0.995. There would therefore be almost no change of the regression results if different versions of the predictor representing anthropogenic forcing were applied (despite the obvious differences in the physical effects involved). This is now explicitly mentioned in the manuscript (p. 8, l. 14+)

Regarding the Land use land cover (LULC): We are working with drought indices for the whole Czech Lands calculated from reconstructed temperature and precipitation series. The calculation procedure of none of these indices includes information about LULC. Although it can be an important factor deciding about drought severity and particularly its impacts, effects of LULC on country-wide temperature and precipitation should be limited. In this study oriented on long-term temporal changes it seems to be not an important factor helping us as predictor in the regression analysis of drought indices series.

a.2- Regarding internal predictors, the NAO is argued to be important but has not been used. Even if it has been described in previous works, it is relevant to see in this approach how much variability do ENSO or PDO account for from the residuals once the NAO has been taken into account. Do the results of the analysis concerning the presently used internal predictors change if the NAO index is used? There are some millennium long index reconstructions that would allow for this exercise. I think there is no point in looking only at Pacific indices without considering a potential larger explanatory variable like this one.

Response R3-2: Our original intention was to concentrate on mid-to-long-range variability in the drought series, i.e. oscillations typically slower than the dominant variability of NAO. Moreover, the strong relation between central European drought regime and NAO phase has been established by various prior studies, hence we considered it to be less interesting for the current analysis. Since both Referees 1 and 3 expressed their interest in the NAO-related effects, in the revised version of the paper, results involving NAO reconstructions by Luterbacher et al. (2002), Ortega et al. (2015) and Trouet (2009) have been included. The results in Figs. 4 and 5 have been updated to show regression coefficients related to NAO in addition to the previously considered predictors; the Results, Discussion and Conclusions sections have been expanded to include analysis of the NAO-related links.

b) Methodological issues There are three ideas that I would like to bring here. One is the linear vs non-linear character of the influences that the paper tries to assess. Another one is the power of the approach used herein related to the covariance structure pursued by the analysis in view of the properties of the predictors. Finally, and related, the collinearity of some predictors.

b.1 Regarding the first one, this is commented in the first paragraph of Sec. 3. I have no reservations against the possibility of nonlinear interactions being relevant. I think it is though important and has value, to study the linear relationships. It is also important to study it in a solid way so that we minimize the danger to loosely argue that everything we cannot explain with a linear approach is due to the limited character of its 'linearity' and probably due to nonlinear interactions.

> **Response R3-3:** We seem to be in agreement with the referee; the mention of nonlinear approach was meant to provide a methodological context while also giving rationale for using linear version of regression for analysis of links in an inherently nonlinear system.

b.2 Regarding the second one, the multiple linear regression is a valid approach to analyze the linear covariance structure in the data. Now, for that purpose, the variables used as predictors like CO2 or, for that case, if additional GHGs+aerosols would (and should) be considered, since these variables present very low variability at high and mid frequencies, one has to be careful in how to handle them in terms of covariance. For instance, a positive coefficient with temperature in the instrumental period means that both temperature and CO2 show positive trends… but any variable showing a positive or a negative trend would show association for that matter. The limited meaning of correlating preindustrial CO2 (+GHGs+aerosols) must be commented and the limited interpretation of correlating trends in the industrial period also should be argued and improved by including other GHGs and aerosols in a meaningful way.

> **Response R3-4:** This is definitely true, and admittedly under-explained in the original manuscript. The inclusion of a trend-like variable (CO_2 concentration in the original version of the manuscript, composite GHG forcing in the revised one) was meant to provide a predictor potentially approximating long-term evolution observed in the drought indices. Naturally, despite the similarity in shape (and thus statistical significance of the link detected for some of the drought indices), the formal relationship does not prove causal relation. While we commented on this in the original version of the text ('Even considering that statistical attribution analysis can only reveal formal similarities and cannot verify the causality of the links detected …' in the Conclusions), and referenced supporting evidence pointing to a physical link between droughts and anthropogenic forcing (the second paragraph of Discussion), the potential for mis-attribution has now been more explicitly emphasized in the revised manuscript (2nd paragraph of the Discussion, p. 12, l. 2+).

b.3 Some of the predictors (eg. AMO, PDO) show covariability. How is this addressed in the analysis and how does this influence the results? Explaining which type of multiple regression approach would be important for this point.

> **Response R3-5:** For the AMO and PDO representations based on the Mann et al. (2009) temperature reconstruction, this was actually addressed (in the Discussion section) by employing a simple form of principal component analysis, allowing to better assess the role of the common component in these predictors and of their difference. In the revised manuscript, the respective

results are now shown in more detail, including the graphs of the regression coefficients pertaining to predictor configurations involving only AMO or only PDO (Figs. S1b, S1c).

Please note also that (multi)collinearity of the predictors results in increased variance inflation factor for the regression coefficients (and thus wider confidence intervals). Since this is an inherent feature of multivariable regression, we did not comment on it specifically; the effect can, however, be seen from Figs. 4 and 5, and it is mentioned in the context of the AMO/PDO collinearity (p. 14, l. 5+).

c) Residuals This is also a rather methodological issue. If the purpose is to statistically describe drought with a multiple linear regression approach, the behavior of the residuals should be discussed. The authors should show estimation of drought variability from the predictor variables, explained variances and some convincing arguments that part of the variability is being reproduced by the predictors used.
I recognize this point, GC1, is rather long. It should probably be treated as independent points. Nevertheless I think it is important and would like to see the arguments for all these. Some specific comments will also follow below.

Response R3-6: The analysis of regression residuals was performed when designing the optimum setup for the moving-block bootstrap. The only noteworthy feature (aside from the approximately AR(1)-consistent persistence structure) was a presence of a weak and rather unstable 22-year-period oscillation (possibly an imprint of the 22-year cycle in solar activity, but inconsistently present throughout our analysis period). This is now mentioned and discussed in the revised version (Discussion, p. 15, l. 32+). Graphs illustrating residual variability have been included in the Supplement (Fig. S4), along with charts of the residual autocorrelations.

As for the explained variances and evaluation of the regression results, R^2 values have been added to the results in Figs. 4 and 5 in the revised manuscript, and sample graphs illustrating regression-estimated components pertaining to individual predictors have been included in the Supplement, as Fig. S5. Regarding the reproduction of variability by our predictors: Please note that prominence of individual explanatory factors is evaluated through statistical significance of the respective regression coefficients, regardless of the overall R^2 – an approach that we believe to be consistent with our primary aim, i.e. identification of forcings and large-scale factors influential in establishing the drought regime of the Czech Lands (as opposed to an attempt to construct a predictive model reproducing the series with as much variability as possible).

GC2 Mechanisms As it stands, the approach of the manuscript is to argue on the basis of the regression coefficients. This is quite extreme in its present state. Even in the discussion part, a relatively aseptic account of the results of other authors are provided in this sense. However a more mechanistic based approximation discussing the rationale behind the statistical relationships that may be found is needed.

Response R3-7: Note, please, that most of the connections highlighted in our analysis represent rather weak (albeit sometimes statistically significant) tendencies, which are difficult to assign unambiguously to specific mechanisms (especially considering that no observational data exist that could be used for analysis of global circulation patterns over the full period of the last five

> centuries, and that dynamical models are still rather unreliable in capturing some of the relevant factors, including the sources of multidecadal climate variability). This is further complicated by often mutually inconsistent or contradicting accounts regarding the effects and mechanisms of some of the relevant forcings/variability modes in the existing literature. Assessment of the possible factors behind our results would therefore be quite speculative on our part. Future, more topically focused (and methodically wider) analysis may bring better understanding of the relevant questions; such an effort would however go beyond the intended scope and aim of our present study.

GC3 Temperature and precipitation What does having temperature and precipitation add in this analysis? I don't mean to be unconstructive... just that if it is included in the analysis pursuing a more in depth understanding of drought, the reader should understand why they are there. What gain in our understanding do we get from including temperature and precip and analyzing them as predictors? Would it be of use including them in one exercise as predictands and assess their relative influence on drought?

> **Response R3-8:** Temperature and precipitation data were used for calculation of the drought indices themselves (as explained in Sect. 2.1), and their behavior is therefore crucial when discussing their combined effect in the drought descriptors.

GC4 Section 5: PCA analysis The strategy for the PCA analysis in page12 should be described (already in the methods section), as well as it is purpose and results presented in the text... unless the results are rendered invalid or not useful. If the analysis provides some valuable insights within this ms, it should be shown.

> **Response R3-9:** We did not mention PCA in the Methods section, as it was only employed as a supporting technique in a small part of our analysis (and we assumed its general principles to be well-enough known to not require introduction). In the revised version, the transformation of the AMO/PDO pair is introduced simply as a calculation of their mutual mean and difference; PCA is now only mentioned as an alternative way to produce the same result. The results based on analysis of principal components are now presented directly instead of just mentioned in the text (Fig. S1c in the Supplement).

GC5 Section 5: discussion The Discussion section provides a wealth of information on different results from various papers. However, in my opinion it misses a bit some purpose or direction. Actually, it also reports on results (e.g. GC4) that are not shown although they permeate to the conclusions. This is not recommendable. I suggest to pass any results clearly to the parts of the paper to make clear the objectives, methods and analysis of the results. Having a Discussion part or a Conclusion and Discussion makes sense to put the results of the present ms in view of past literature and state clearly what we learn from it. I would advise the authors to modify this section in this sense.

> **Response R3-10:** The results originally just mentioned (but not shown) in the manuscript are now included fully, either in the main paper or in its Supplement. The Introduction and

> Discussion have been modified to paint a clearer picture of our main objectives: to assess the existence of links between Czech drought indices and climate forcings or activity of large-scale internal variability modes, and to investigate the properties of the existing reconstructions.

Specific comments

SC1 Title: '... large-scale climate drivers' If we understand 'large-scale climate drivers' referring to modes of circulation, shouldn't the title also include those? E.g. ' Longterm variability of droughts in the Czech Lands due to external forcing and large scale climate drivers' ?

> **Response R3-11:** Based on this comment and suggestions of Referee 2, we changed the title to "Long-term variability of drought indices in the Czech Lands and effects of external forcings and large-scale climate variability modes"

SC2 Page 2, l 17: 'Internal forcings' I think the use of this concept is not adequate in the manuscript. We relate forcing factors to changes in the energy of the system and, therefore, external in nature. I agree with using the terms internal/external drivers or external forcings, but not internal forcings.

> **Response R3-12:** The terminology has been changed in the revised version of the text to avoid use of the term 'forcing' for factors originating from internal climate dynamics.

SC3 Page 3, l 31: 'Missing monthly precipitation figures ...' I don't understand what is meant here by 'missing' figures in Dobrovolny et al (2015).

> **Response R3-13:** Changed to "Missing monthly precipitation totals in …"

SC4 Section 2: Figure 1 I haven't found a reference to Figure 1 in the ms. Check on this please. Regarding this figure and the presentation of drought, in Section 2 there is some description of differences in definitions among the different drought indices used in the text. I think some comment on the available reconstructions are pertinent. There is a paragraph in page 2 (l 21-30) describing the origin of the series. Can the authors provide any thoughts on whether the different definitions really play a role or basically the same information is available, also considering the source data for the reconstructions. Can we anticipate any added value of using these three indices instead of one in this work?

> **Response R3-14:** In order to express various sides of droughts, there exists a great number of different drought indices. SPI, SPEI and PDSI represent those which are used in description and quantification of droughts most frequently, and they are also used for estimating impacts of agricultural and hydrological droughts. While there are obvious similarities between the respective time series (due to precipitation sums being the key factor shaping all of them), each of the indices represents slightly different approach. As mentioned by the referee, these are briefly summarized in Sect. 2.1, along with references to more comprehensive sources. Based on the differences found during our analysis, their individuality seems strong enough to justify inclusion of all three indices.

> Reference to Fig. 1 has been added to the text, to the first paragraph of Sect. 2.1.

SC5 Section 2.2: forcings I think it is desirable to place this forcing in the context of PMIP3 and PMIP4 forcings. The authors will find longer reconstructions of this forcing spanning the millennium that have been used to detect solar forcing on temperatures for instance since the 14th century (Schurer et al 2013). Maybe these can be better options for predictors than the one used in the ms (1610-present) Schurer, A., G. Hegerl, M. E. Mann, S. F. B.+Tett, and S. J. Phipps, 2013: Separating forced from chaotic climate variability over the past millennium. J. Clim., doi:10.1175/JCLI-D-12-00826.1.

> **Response R3-15:** We are grateful for the suggestions; in the revised version of the analysis, a recently published TSI reconstruction by Lean (2018) has been used to represent solar activity (providing full coverage for the 1501-2006 period). The previously employed TSI data by Coddington et al. (2016) have been retained as an alternative solar-related predictor.

SC6 Section 5 L 30 '... the increase in the ambient CO2 post 1850 is clearly correlated with the increased probability of drought... while during the pre-instrumental period such link does not manifest. The trend in CO2 in the industrial period is just one degree of freedom. Please recall the comments GC1b

> **Response R3-16:** True, but note please that while we mentioned the existence of a correlation, we did not interpret it as a causal relation, only noted the possibility of one (please see also our Response R3-4).

Technical corrections, typing errors,etc:
TT1 Page 6, l 8: '...results...standardized regression coefficients...' In an simple regression these would be, by definition, correlation coefficients. How does this differ in this analysis from correlations? Some methodological details on the multiple regression approach taken is advisable. Does it account for covariability in the predictors? Etc...Please provide more explanation of the relevant aspects in the ms.

> **Response R3-17:** Indeed, in simple (univariable) linear regression, standardized regression coefficient corresponds to correlation between predictor and predictand (and, in absolute value, to square root of the coefficient of determination). In multiple regression, however, no such straightforward relation exists for individual predictors. Standardization of the coefficients is used to make them more comparable mutually (among different predictors as well as among predictands), thought, admittedly, this representation does not directly convey information about the magnitude of the responses. In the revised version, the responses are therefore also shown in the form of predictor-specific time series generated for a selected regression configuration (Fig. S5 in the Supplement).
>
> As for covariance of the predictors, its effect is reflected in the size of the confidence intervals for individual predictors (please see also our response R3-5).

TT2 Page 2, l 20: '...that increase...' substitute by '...that the increase...' This is just an example. I have found a few of those. I think the text is easy to understand in general. However, I would recommend it would be revised for editing/English

Response R3-18: Selected example corrected. The English of the manuscript was checked and corrected by a native speaker, Mr. Tony Long. The language correction was repeated in the revised text once again.

Long-term variability of ~~droughts~~drought indices in the Czech Lands and effects of external forcings and large-scale climate ~~drivers~~variability modes

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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 forcings and internal climate ~~forcings~~variability modes 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 selected climate variability modes~~ with pronounced inter-annual to inter-decadal variability~~ (El Niño–Southern Oscillation – ENSO, Atlantic Multidecadal Oscillation – AMO, Pacific Decadal Oscillation – PDO, North Atlantic Oscillation – NAO), 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, and strong connection to the NAO, temperatures in the AMO and (particularly) 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~~structure of their shared periodicities 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~~This is also valid for the territory of the Czech Republic where droughts, apart from floods, constitute the most important natural disasters, with significant impacts upon various sectors of the national economy, such as agriculture, forestry, water management, and tourism/recreation. Since the Czech Republic lies on a continental divide with rivers flowing out of its territory, it depends on atmospheric precipitation alone for its water supply. Although certain extreme droughts with important socio-economic and political impacts are known from the past, such as the drought of 1947 (Brázdil et al., 2016b), studies performed in recent years show the Czech climate has become increasingly dry in the past 2–3 decades, expressed in terms of higher frequency of extreme droughts with significant consequences (e.g. Brázdil et al., 2015b; Zahradníček et al., 2015). The abundance of long-term instrumental meteorological observations 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, in the European area (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).~~2015) as well as other areas of the world (e.g. Dai, 2011; Spinoni et al., 2014; Ryne and Forest, 2016; Wilhite and Pulwarty, 2018). 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,~~studies investigating drought indices for the instrumental period in Europe (e.g. van der Schrier et al., 2007, 2013; Briffa et al., 2009; Sousa et al., 2011; Todd et al., 2013; Spinoni et al., 2015; Haslinger and Blöschl, 2017) and other areas of the world (e.g. Dai, 2011; Spinoni et al., 2014; Ryne and Forest, 2016; Wilhite and Pulwarty, 2018), 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~~climate forcings and large-scale internal ~~forcings~~variability modes, 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 the 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 and large-scale climate variability modes in series of drought indices in the Czech Lands during the 1805–2012 period. ~~They~~The authors 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~~). In addition to an analysis of potential drought-relevant links in the ~~emphasis on manifestations of inter-decadal changes and~~ climate system, attention is paid to their ~~possible drivers.~~temporal stability and (mis)match of results based on climate reconstruction data from different sources. Regression and wavelet analysis ~~were~~are 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~~explanatory factors and their interaction in Section 5. The last section then delivers a number of concluding remarks. Additional materials are presented in the electronic Supplement.

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 country-wide drought indices were employed, each of them embodying a different strategy for defining dry/wet conditions~~.~~ (Fig. 1):

(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. Documentary data comprised descriptions of weather and related phenomena from a variety of documentary evidence, some of it individual, some of it of an institutional character, such as annals, chronicles and memoirs, weather diaries (non-instrumental observations), financial and economic accounts, religious records, newspaper and journals, epigraphic sources, and more. Such data in the Czech Lands cover particularly, at varying degrees of density, the period from AD 1501 to the mid-19th century, but continue even to the present time. The spatial density of such data changes over time, depending on the availability and extraction of existing documentary sources. All the data collected were critically evaluated with respect to possible errors in dating or spatial attribution and were used for interpretation of monthly-weighted temperature and precipitation indices on a 7-degree scale, from which series of seasonal and annual indices were created (for more details of the use of documentary data, its critics, analysis and interpretation, as well as creation of series of indices in historical climatology, see Brázdil et al., 2005, 2010). Such data were further used as a basic tool for temperature/precipitation reconstructions. 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~~documentary-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~~totals 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~~ As a result, a 100-member ensemble of distributions of monthly precipitation totals for ~~every~~each season and year ~~in~~ was obtained. These distributions were then applied to calculation of indices for every year in the 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~~defining factors 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,~~2 (external forcings) and 3 (internal climate variability modes), 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~~A large part of the observed changes may be attributed to variations in the concentrations of long-lived greenhouse gases~~,~~ (GHGs), carbon dioxide (CO_2) in particular, but also methane (CH_4) and nitrous oxide (N_2O) (Stocker et al., 2013). Considering that past ~~CO_2~~GHG concentrations are accessible to relatively accurate reconstruction using ice cores, their ~~annual values were~~combined radiative forcing was considered as a potential formal descriptor of the long-term trends in the drought series studied ~~here~~herein. The time series of annual GHG forcing by Meinshausen et al. (2011) was used for the period since AD 1765, and extended back to AD 1501 using the CO_2, CH_4 and N_2O 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/).~~online database of the Institute for Atmospheric and Climate Science, ETH Zurich.

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~~(TSI) by Lean et al~~., 2016~~. (2018) was used as the primary descriptor of solar activity. ~~Since annual solar activity~~With data ~~for the earliest part of the period analyzed were not~~ available~~, the tests involving solar forcing were carried out~~ from AD 850 onwards, the TSI values were used for the period 1501-2006 herein. An alternative TSI dataset by Coddington et al. (2016) was also employed, for ~~a shorter interval, covering~~ the ~~years~~ 1610–2006 period.

Unlike variations in solar activity or concentrations of ~~greenhouse gases~~GHGs, 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), triggering summer cooling over Europe and winter warming over northern Europe (Fisher et al., 2007), but ~~with rather~~exhibiting just 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 (AOD) 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~~3a). 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~~6c, 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~~multiproxy reconstruction of annual temperatures in the AMO region by Mann et al. (2009) was employed~~.~~ for the 1501–2006 period, as well as tree-ring-based AMO reconstruction by Gray et al. (2004), available for the 1567–1990 period (Fig. 3b). Again, due to the presence of a strong trend component in the ~~time~~Mann et al. 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. Additional PDO index reconstructions by MacDonald and Case (2004) and Shen et al. (2006) were also included in our analysis for the 1501–1996 and 1501–1998 periods respectively (Fig. 3c).

Unlike AMO, PDO and ENSO, dominated by mid-to-long-term temporal variations, the North Atlantic Oscillation (NAO) constitutes a faster-oscillating climate mode, although the presence of long-term components has also been reported in some of its indices (e.g. Trouet et al., 2009; Ortega et al., 2015). For the analysis herein, three reconstructions of NAO activity were tested (Fig. 3d). The NAO index series by Luterbacher et al. (2002), based on various Eurasian documentary and proxy data, is available for AD 1659–2001 in monthly time-steps and for AD 1500–1658 in seasonal time-steps. For the purposes of this study, it was also analyzed in the form of annual NAO index values, extended to the year 2006 by the instrumental NAO index data by Jones et al. (1997). The annually-resolved multi-proxy winter NAO reconstruction by Ortega et al. (2015) was adopted for the 1501–1969 period. Finally, a reconstruction of decadal winter NAO variability by Trouet et al. (2009) was used for the 1501–1995 period.

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~~detrimental, given their higher degrees of freedom and higher sensitivity to ~~inhomogeneities~~non-homogeneities 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~~values constituting mean for the entire year, or as ~~sequences of~~ values pertaining to a single season of each year in the usual climatological sense~~ (the~~: winter (DJF), spring (MAM), summer (JJA) or autumn (SON). 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~~. The basic analyses were carried out for the whole 1501–2006 period; more limited time ranges were, however, used for some of the tests involving specific predictors with shorter temporal coverage. 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 used. The results are presented in the form of standardized regression coefficients in Figs. ~~applied~~4 (annual series) and 5 (season-specific series), i.e. equivalent to a setup with both predictand and predictor series converted in linear fashion to zero mean and unit variance.

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~~– AR(1), 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~~Regression-estimated 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 associated with the ~~CO$_2$ concentration~~GHG forcing 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$_2$~~GHGs 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~~1501–1850 era (Fig. 4b), in which the ~~CO$_2$~~GHG signal is mostly featureless. This pattern also appears for individual seasons, with the ~~CO$_2$~~GHG–temperature link at its relative strongest during SON ~~and weakest during DJF~~ (Fig. 5). The formal association of ~~CO$_2$ concentrations~~GHG forcing 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$_2$~~GHG forcing series ~~were~~was replaced with a predictor representing ~~total greenhouse gases forcing~~ just CO$_2$-related effects, or by total anthropogenic forcing including the effects of man-made aerosols.

There is a lack of ~~any~~significant imprint from solar activity in our target series when Lean (2018) solar irradiance data are used for the 1501–2006 period (Fig. ~~4~~4a). 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~~While a borderline significant response appears for temperature in the 1501–1850 period (Fig. 4b), it disappears when data for 1610–2006 are considered alone, i.e. the period when sunspot data are used in the reconstruction by Lean (2018) (whereas prior to 1610, a more indirect approach is used, utilizing cosmogenic irradiance indices) – Fig. S1e. Non-significance of the imprint of solar activity was also indicated when the Coddington et al. (2015) total solar irradiance series was used as a proxy for solar activity in the 1610–2006 period (Fig. S1d). A statistically significant solar-related signal was also absent in all individual seasons except for SON (Fig. 5).

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~~ still non-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~~especially during summer, when a borderline statistically significant response also appears for precipitation and both SPI and SPEI, indicating 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~~,~~, (Brázdil et al., 2015a), this analysis did not reveal any statistically significant associations within the annual data~~. Such~~ when the ENSO reconstruction by Li et al. (2011) was used, even though there was a ~~lack of~~ slight tendency towards higher temperature during positive ENSO phase (Fig. 4). This tendency was even stronger (and borderline statistically significant~~ responses was obtained from both ENSO reconstructions (~~) for the Mann et al~~.,~~. (2009~~; Li et al., 2011) used herein, despite their distinctly~~) ENSO data (Fig. S1i), regardless of the markedly different temporal variability~~. These results also hold for individual sub-periods. However, in~~ in both reconstructions. 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~~,~~, (Fig. 5), 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~~used.

The Atlantic Multidecadal Oscillation (AMO) index based on the Mann et al. (2009) data was found to be linked to the variability of Czech precipitation, as well as all drought indices during the 1501–2006 period~~.~~ (Fig. 4a). However, its effect is ~~largely absent~~somewhat less prominent prior to 1850~~.~~ (Fig. 4b). A similar response also appears when the AMO reconstruction by Gray et al. (2004) is employed (Fig. S1f), with the statistical significance of the link lower than for the Mann et al. data. The existence of a robust ~~link~~connection is therefore ~~dubious~~uncertain, 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~~.~~, when Mann et al. (2009) data were used as PDO index source (Fig. 4). 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). When the Mann et al. data are replaced with the reconstructions by MacDonald and Case (2005 – Fig. S1g) or Shen et al. (2006 – Fig. S1h), no significant response to PDO index appears for any of the target variables.

Of the NAO index reconstructions employed here, the series by Luterbacher et al. (2002) was found to be associated with the strongest and statistically most significant responses in the 1501–2006 period, as well as in both its sub-periods (Fig. 4). Positive NAO phase correlates with high temperatures and low precipitation totals, and thus negative values of drought indices. In terms of season, this pattern is well-pronounced in MAM and SON, whereas in DJF the link to precipitation and SPI is only borderline significant and no imprint appears for SPEI (Fig. 5). In JJA, the effect of NAO is non-significant regardless of the target variable. The effect of winter NAO was found to be similar for the Ortega et al. (2015) data, although only statistically significant for temperature (Fig. S1k). Finally, the winter NAO index by Trouet et al. (2009) was not associated with a statistically significant response in any of the target variables (Fig. S1j); note, however, that unlike the Luterbacher et al. (2002) and Ortega et al. (2015) series, this reconstruction only captures the long-term variations of NAO, and thus foregoes most of the NAO variability spectrum).

4.2 ~~Coherence~~Shared periodicities between drought indices and ~~forcings~~explanatory factors

Although Brázdil et al. (2015a) demonstrated well-pronounced inter-annual and inter-decadal variations in the Czech ~~spring–summer~~MAM–JJA 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~~or 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~~spectra of ~~the~~both AMO series here, it tests as statistically significant only from the 18th century onwards ~~– Fig.~~

~~6).~~in the Mann et al. (2009) data – Fig. 6d). Nonetheless, partial interactions at specific oscillatory periods are a possibility, potentially detectable through cross-wavelet analysis. The respective spectra are visualized in Fig. 7 (of the drought indices, results for only SPEI are shown, as the cross-wavelet patterns are very similar for SPI and PDSI); additional results for alternative predictors are provided in Fig. S2 in the Supplement.

While an approximately 11-year oscillation is one of the defining features of total solar irradiance series (Fig. 6b), the match with similar periodicities in the Czech drought data is limited to just a few short periods, manifesting mutually quite different phase shifts (Fig. 7a). This outcome supports the conclusions of the regression analysis in Sect. 4.1, indicating the lack of a robust direct link between the central European climate and solar activity variations.

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 (Fig. 7b) and PDO (Fig. ~~7). The patterns~~7c). These are ~~very~~particularly noticeable in the reconstruction by Mann et al. (2009) and quite 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~~oscillations is, however, stable throughout the entire period analyzed; ~~coherence within~~match for 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 may also ~~appear~~be found in the cross-wavelet spectra involving drought indices~~ (Fig. 7 – results~~. However, when the reconstruction by Gray et al. (2004) was used as source for the AMO variability, only ~~SPEI are shown, as the graphs are almost identical~~oscillations in the *c*. 60–100 years range were found to be shared with the Czech drought indices, and manifesting profound changes in phase difference throughout the analysis period (Fig. S2a). Similar behavior was also detected for ~~SPI and PDSI).~~the PDO reconstruction by Shen et al. (2006; Fig. S2c), while no significant periodicity match was found for the PDO data by MacDonald and Case (2005; Fig. S2b).

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~~.~~ (Fig. 7d). 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, again indicating the lack of a systematic stable relationship~~, consistent with the non-significance of the links obtained by the regression analysis.~~ (Fig. S2d).

~~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*.~~No significant match between the oscillations in the NAO index series and the drought indices was found for the short-to-mid periods (it is worthy of note that this result does not imply lack of relationships as such, merely an absence of common periodicities detectable by the wavelet transform). Regions of possible coherence were, however, detected for the longer time-scales. Employing the NAO index reconstruction by Luterbacher et al. (2002), common oscillations with periods of around 70 years were found, especially during the 18th and 19th centuries (Fig. 7e). For the Ortega et al. (2015) winter NAO data, significant common oscillations of *c.* 60–100 years appear for temperature throughout most of the analysis period (Fig. S2e). A similar, even stronger pronounced, pattern of similarities at multi-decadal scales was also found for the Trouet et al. (2009) NAO index, owing to the strong resemblance of the long-term components in the Ortega et al. and Trouet et al. NAO data (Fig. 3d).

~~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~~MAM–JJA 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~~NAO phase and of the aggregate effect of anthropogenic forcing, driven particularly by increasing ~~CO_2~~GHG 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~~AMO 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~~GHGs post 1850 is clearly correlated with the increased probability of ~~drought~~droughts in the Czech Republic, while during the pre-instrumental period such link does not manifest. Even so, it should be emphasized that regression (or, more generally, statistical) analysis does only reveal formal similarities between target and explanatory variables, and cannot prove presence of physically meaningful relationships on its own. This is particularly true in case of signals dominated by simple trends, such as the gradual rise of GHG radiative forcing during the industrial era. Our results should therefore be considered a supportive argument regarding the relationship between the drought regime and the anthropogenic forcing, not a definitive proof of a causal link.

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~~regardless of 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 of the drought indices 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. (2009) series, it may be speculated that the responses in the seasonal data are tied to inter-annual rather than decadal variability. On the other hand, both ENSO predictors employed here, by Li et al. (2011) as well as by Mann et al. (2009), have been linked to a tendency towards higher temperature during positive ENSO phase, although only borderline statistically significant for the Mann et al. (2009) data when the entire period 1501–

2006 is considered. 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~~, most prominent in summer. Our results conform well to the findings by Fisher et al. (2007), who reported a distinct radiative cooling effect of major tropical eruptions during European summer over the last five centuries. The results are also consistent with the ~~findings of~~analysis by Gao and Gao (2017), who ~~analyzed~~studied 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~~MAM and ~~summer~~JJA hydroclimate over Europe and the Mediterranean during the last millennium by Rao et al. (2017) indicated wet conditions ~~occur~~occurring 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~~2016c) 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~~noticeable 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; Sutton and Hodson, 2005; 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 especially in case of Mann et al. (2009) data, 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~~our 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). This similarity is also apparent from the cross-wavelet spectrum between the AMO and PDO series (Fig. S3b), revealing high coherence especially for periods of *c.* 20–30 years and 60–100 years, with relatively stable phase shifts, especially for the latter band. 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~~.~~ (Fig. S1b). On the other hand, AMO alone produces no significant links to drought indices~~.~~ (Fig. S1b). To investigate this behavior further, the AMO~~-~~/PDO pair was replaced with their ~~transformation by~~ mean value and their difference (note that this setup formally corresponds to the outcomes of unrotated principal component analysis~~. In this setup, the first principal component (PC1; representing~~ applied to a bi-variate system consisting of the AMO and PDO index series, with the mean value responsible for 88% of total variance~~) corresponded to the arithmetic mean of the AMO and PDO series, while~~ of the ~~second component (PC2;~~ AMO/PDO pair and the difference responsible for 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.~~the AMO-PDO difference (all responses statistically significant at the 99% level) rather than their common value (Fig. S1c). This suggests that the ~~difference~~contrast between the ~~temperatures~~temperature anomalies in the northern Atlantic and northern Pacific, ~~rather than~~in addition to their ~~common concurrent~~individual variability, ~~is~~may be influential in the context of the ~~interdecadal variability~~inter-decadal components of central European droughts.

In contrast with the data by Mann et al. (2009), the effects of AMO/PDO on Czech drought indices were less pronounced when other reconstructions were employed. In the case of AMO, use of the Gray et al. (2004) series revealed tendencies qualitatively similar to the AMO Mann et al. (2009) predictor (higher precipitation and higher drought indices for positive AMO phase, and negative temperature anomalies), but with lower statistical significance (Fig. S1f). While both reconstructions are only moderately correlated ($r = 0.29$ over the 1567–1990 period, increased to $r = 0.39$ when the shorter-term oscillations were removed from the Gray et al. (2004) data by a 11-year running average), there is a distinct similarity in the oscillations in the 60–100-year period band (Fig. S3c).

The similarity of individual reconstructions was even weaker for PDO, with mutual correlations of the three reconstructions (Mann et al., 2009; MacDonald and Case, 2005; Shen et al., 2006) not exceeding *r* = 0.17 over their respective overlap periods. Clear differences between the reconstructions are also apparent in the cross-wavelet spectra (Fig. S3c). While some regions of common oscillations exist, especially in the *c.* 20–30 years and 60–100 years period bands, the phase shifts vary substantially. The contrasts among individual reconstructions should not be surprising in view of the major differences in data inputs employed for their creation (global multiproxies for Mann et al., 2009, east China summer rainfall for Chen et al., 2006, and North American tree-ring data for MacDonald and Case, 2005). Choice of reconstruction obviously plays a pivotal role in an analysis such as ours; considering that the Mann et al. (2009) PDO series was the only one manifesting statistically significant links to the Czech drought, temperature and precipitation data, and that several other key series are available as parts of the same dataset (including the mean hemispheric temperature), this dataset seems most suitable for future analyses concerned with central European climate.

Clear responses of all drought indices as well as temperature and precipitation to NAO were detected for the Luterbacher et al. (2002) data. The existence of such relationship is hardly surprising, considering the pivotal role of NAO in establishing the central European climate. Of perhaps more interest may be temporal stability of this link, especially during the pre-instrumental period. While the cross-wavelet transform only suggests potential coherence for periodicities around 70 years, especially for temperature (Fig. 7e), the dominance of relatively fast inter-annual variability in the NAO data allows for the regression mappings to be split to more segments than in our other tests. In Fig. S8, regression coefficients pertaining to NAO are therefore shown for the individual centuries. While there are some differences among these individual sub-periods, the links are statistically significant for all of them in case of SPEI and temperature. This outcome not only confirms presence of links between droughts and NAO, but also verifies suitability of the Luterbacher et al. (2002) reconstruction for their analysis, even in the early parts of the data and regardless of certain degree of heteroscedasticity in the Luterbacher et al. (2002) series (manifesting through lower variance in the early parts of the NAO series for all seasons but DJF). The results obtained with the Luterbacher et al. (2002) data were also largely confirmed by the Ortega et al. (2015) reconstruction for the 1501-2006 period, although statistical significance of the links to Czech drought indices was generally lower (Fig. S1k); also, just a comparison for DJF was performed, given the winter-specific nature of the Ortega et al. (2015) NAO index series.

It should be mentioned that the fraction of variance explained by the regression mappings (R^2) is quite low in ~~all~~some of the cases presented above: it ~~does not exceed~~is about 0.~~05~~06 for ~~drought indices~~SPI or precipitation at annual resolution in the 1501–2006 period~~.~~ (Fig. 4a). A slightly higher value (R^2 = 0.~~14~~11) was achieved for the temperature~~ series, mostly due to the match of long-term trends~~-sensitive SPEI, and even higher (R^2 = 0.28) for temperature ~~and of CO_2 concentration. Somewhat higher~~ itself. Higher R^2 was also indicated for some individual sub-periods, especially 1851–2006~~.~~, with R^2 = 0.11 for SPI and R^2 = 0.21 for SPEI (Fig. 4c). 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~~.~~ (see Fig.

S5 for an illustrative example, visualizing regression-based estimate of the annual SPEI values and the relevant predictor-specific components). 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 (possibly driven, at least partially, by temperature variations in the AMO and PDO regions) or episodic perturbations (volcanic activity). No distinct structures beyond the AR(1)-consistent autocorrelation decay were found in the regression residuals (Fig. S4), with the exception of possible traces of a 22-year cycle in the PDSI residual series and a weak tendency towards positive autocorrelations for temperature. While these may indicate the presence of unaccounted-for effects of a double solar cycle (previously reported for Italian droughts by Diodato and Bellocchi, 2011) and/or an unexplained trend component, the statistical significance of these residual structures is low.

~~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.~~

The interactions among the explanatory variables, often manifesting through (multi)collinearity of the predictors, are among the potentially critical aspects of multivariable regression analysis. While this study addressed the high correlation between the AMO and PDO predictors based on Mann et al. (2009) data, there are other possible relationships worthy of attention. Additionally, the links may be subject to time-delayed responses of the target variables to the predictors or delayed responses of internal variability modes to external forcings. To investigate these, cross-correlation functions were examined between the target variables and predictors with pronounced inter-annual variations, as well as between the selected predictors themselves. No prominent short-term time-delayed responses were detected regarding the direct effects of solar or volcanic activity (Fig. S6); if present, distinct extrema of cross-correlations only occurred for concurrent, non-lagged series. Additionally, presence of long-term components was detected in the solar-related autocorrelation functions. Since these stem from interaction of long-term trends in the time series and cannot be reliably interpreted via correlation/regression techniques, they were not taken into account in our analysis. Attention has also been paid to the possibility of delayed responses to volcanic or solar activity in the NAO index, considering the previous reports of positive NAO phase during several years following large volcanic eruptions (Ortega et al., 2015; Sjolte et al., 2018). No clear delay was detected for the analysis setup herein (Fig. S7). In case of the NAO-TSI cross-correlation, a maximum was indicated for lag of 2-3 years. While this behavior may be indirectly related to the 5-year delayed circulation response to solar activity reported by Sjolte et al. (2018), its magnitude was rather low in our analysis setup. Finally, to assess whether part of the variability generated by external forcings may be mediated through predictors pertaining to internal climate variability modes, regression analysis was carried out with external forcings only (Fig. S1a). The resulting responses were found to be very similar to the setup with all seven predictors (Fig. 4), suggesting just limited direct linear imprint of external forcings in the predictors representing influential internal climate variability modes in our analysis.

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, and an even finer division ~~would prove difficult in~~was employed to study the ~~light~~stability of the ~~relatively~~NAO-related links, such an approach is problematic for the factors dominated by variations at long ~~characteristic times of some of the processes involved~~periods (such as AMO~~) compared to the length of the time series available.~~). In this regard, cross-wavelet transform ~~may provide~~provided some extra insight; it appears that while periodic oscillations do not dominate Czech drought indices, some specific 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~~.~~ and appear for multiple target/explanatory variables. To better ~~describe~~understand these links and their implications, a transition to more complex regression methods ~~may~~will 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 and large-scale internal variability modes 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$_2$~~GHGs 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~~pre-instrumental and ~~recent~~instrumental 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 Czech 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 (especially) PDO appear to be tied to decadal and ~~multidecadal~~multi-decadal 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~~phases 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~~as it only ~~with~~appears for some of the ~~specific~~ AMO~~ and ~~/PDO reconstructions ~~used.~~in our analysis.

~~Finally~~(iv) NAO was reaffirmed as a powerful driver of drought variability in this analysis. For the primary NAO reconstruction in the tests herein (Luterbacher et al., 2002), not only were links detected for all the drought indices as well as temperature and precipitation, but their statistically significant presence was confirmed throughout the entire analysis period, including its earliest parts.

Overall, 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~~documentary- 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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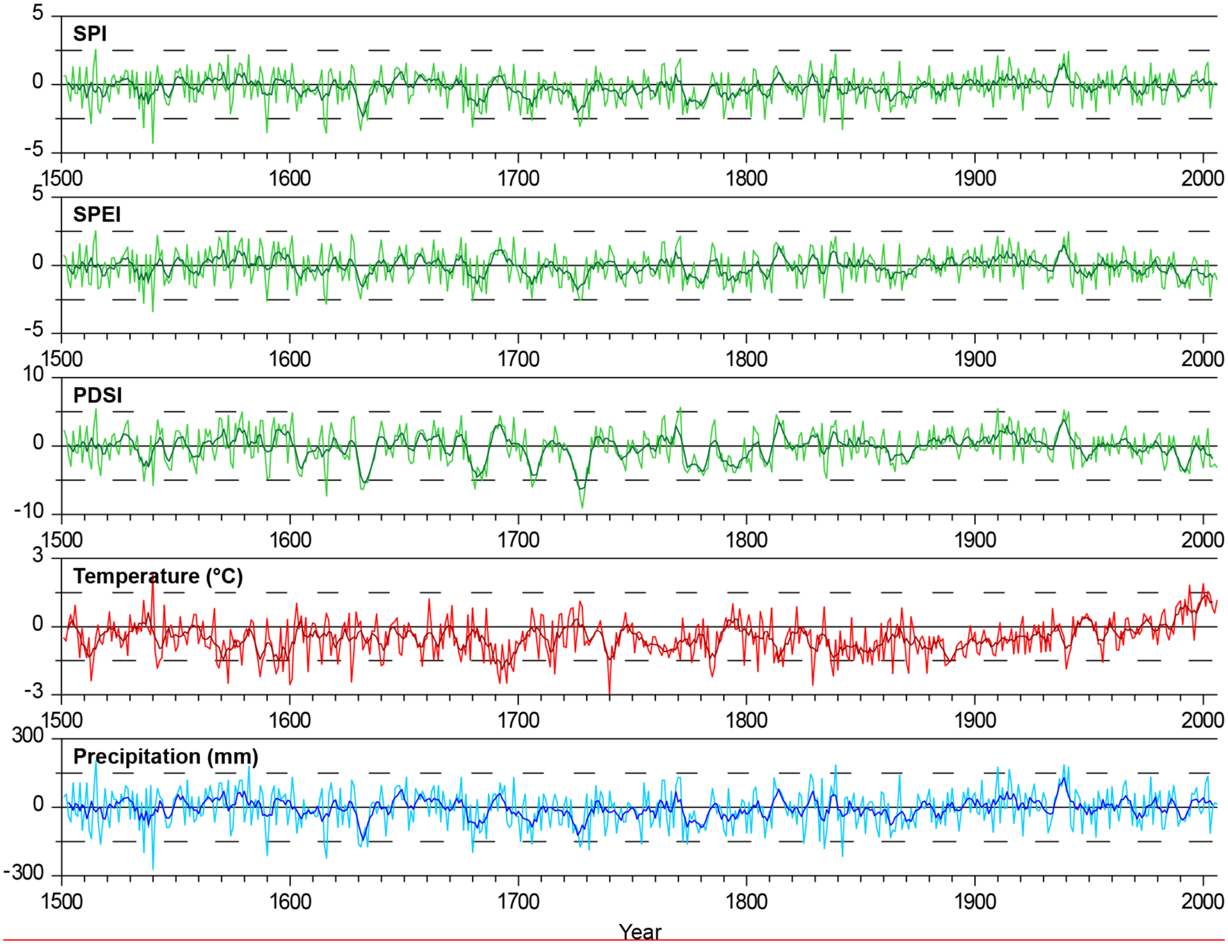

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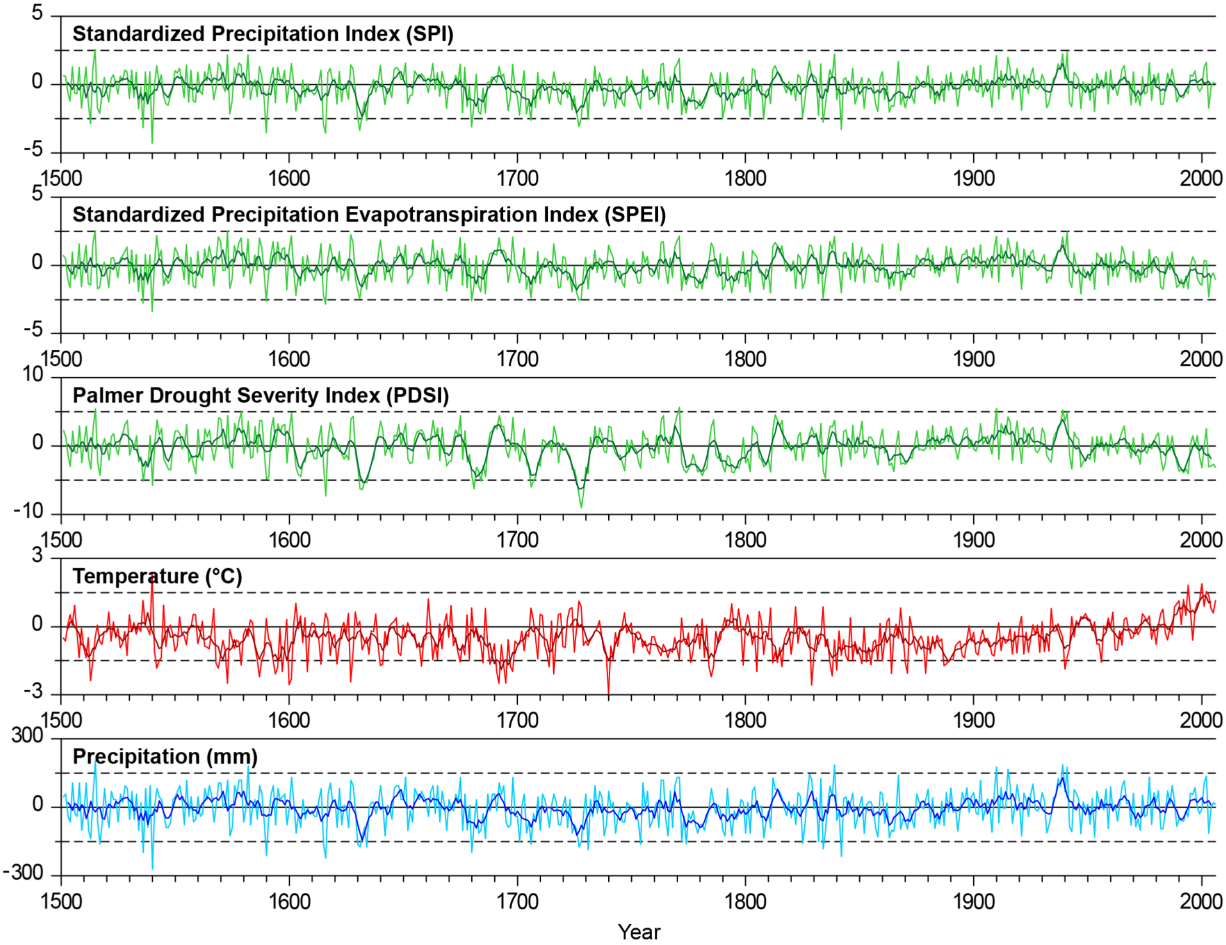
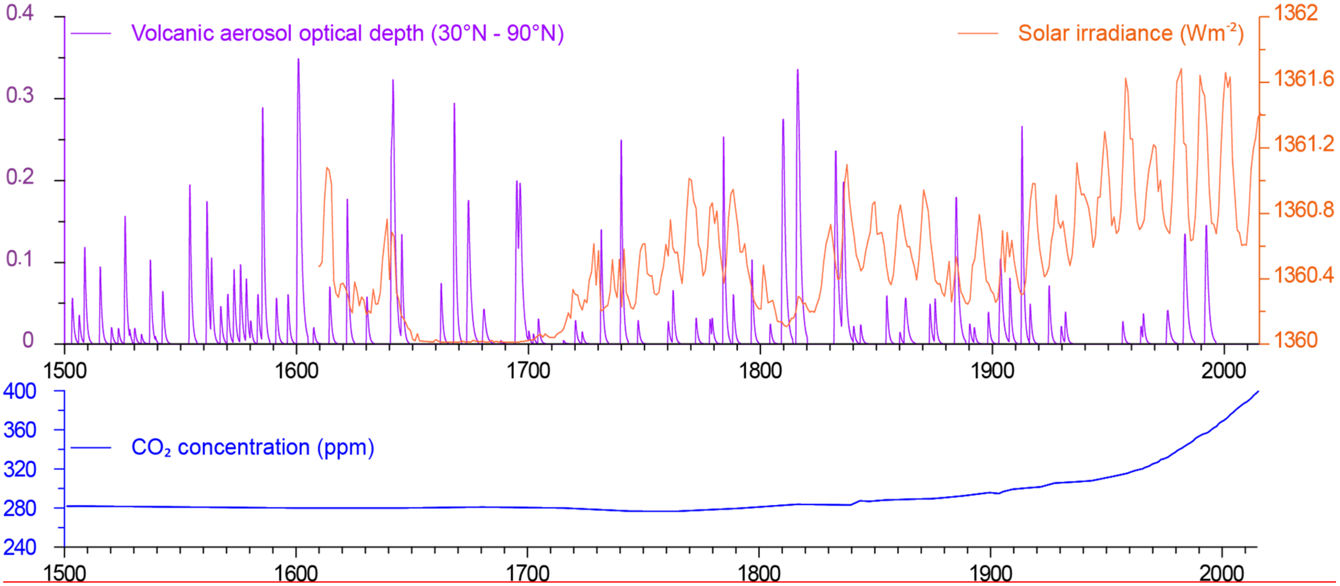


Figure 1. Fluctuations in annual drought indices, temperature and precipitation anomalies (w.r.t. 1961–1990 reference period) for the Czech Lands in the ~~AD~~ 1501–2006 period; smoothed by 11-year running means (darker lines).



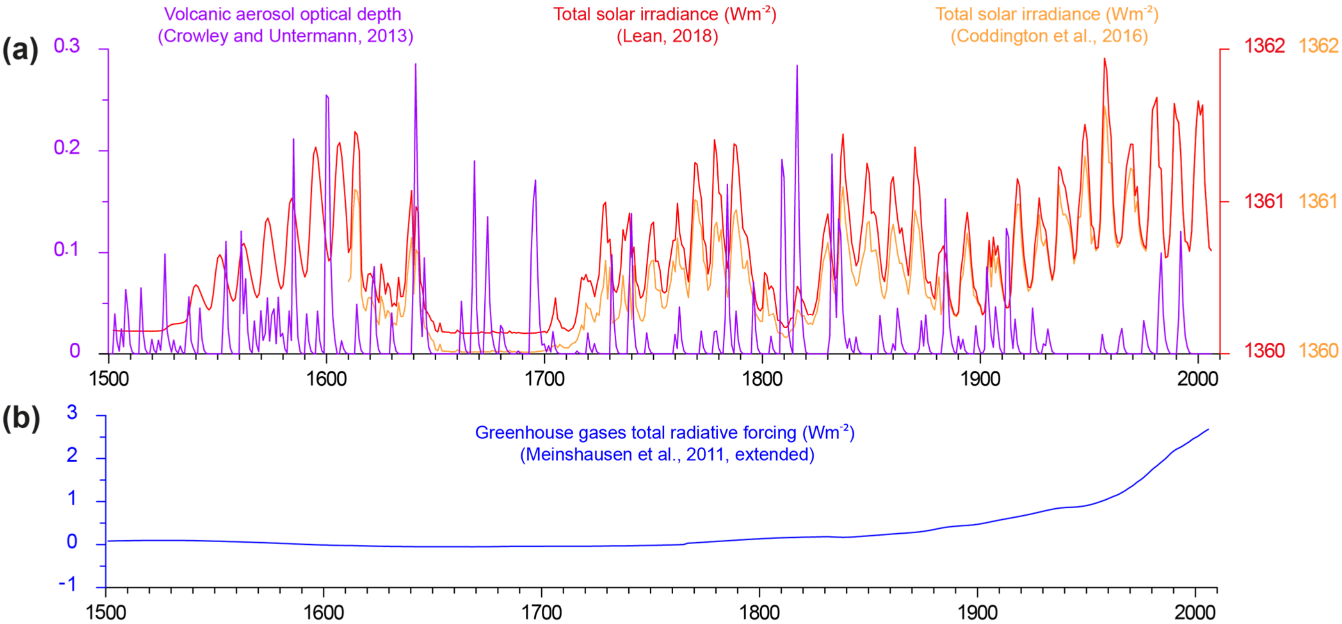
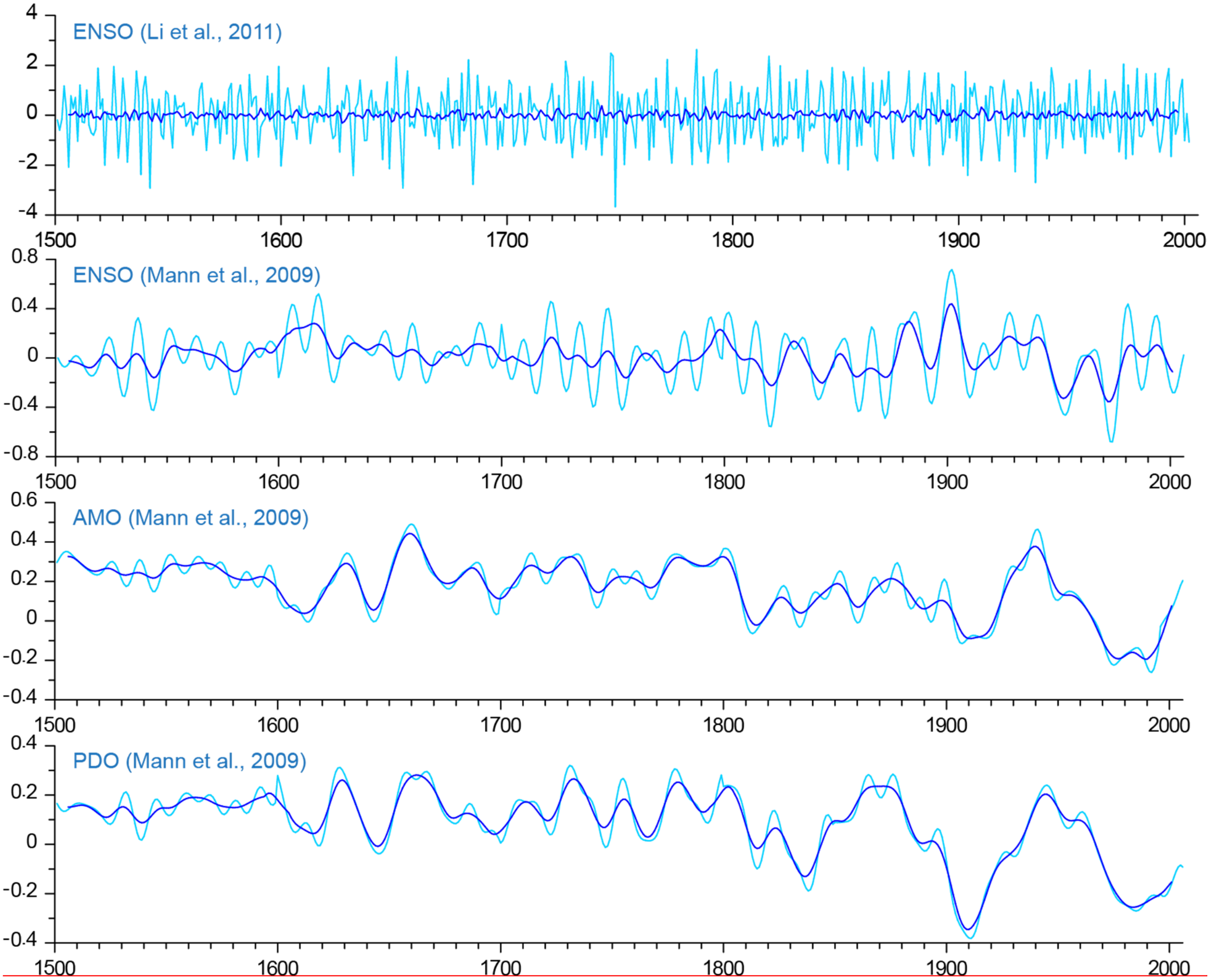


Figure 2. Fluctuations in the annual series of external forcing descriptors~~ (~~: (a) volcanic aerosol optical depth ~~for 30°N–90°N,~~and total solar irradiance~~ and CO$_2$ concentration).~~, (b) greenhouse gases radiative forcing.


ENSO (Li et al., 2011)
4
2
0
-2
-4
1500
1600
1700
1800
1900
2000
ENSO (Mann et al., 2009)
0.8
0.4
0
-0.4
-0.8
1500
1600
1700
1800
1900
2000
AMO (Mann et al., 2009)
0.6
0.4
0.2
0
-0.2
-0.4
1500
1600
1700
1800
1900
2000
PDO (Mann et al., 2009)
0.4
0.2
0
-0.2
-0.4
1500
1600
1700
1800
1900
2000

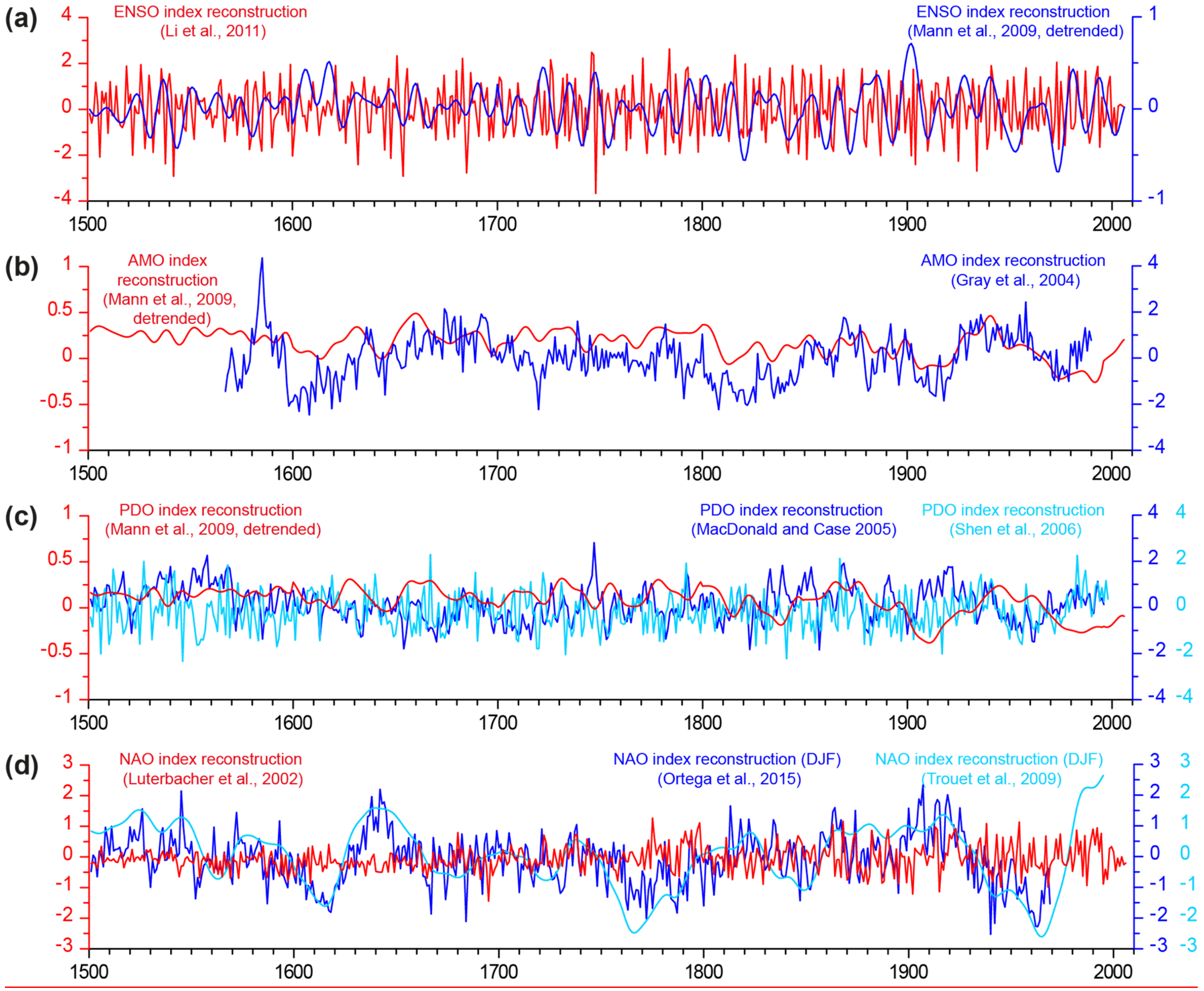
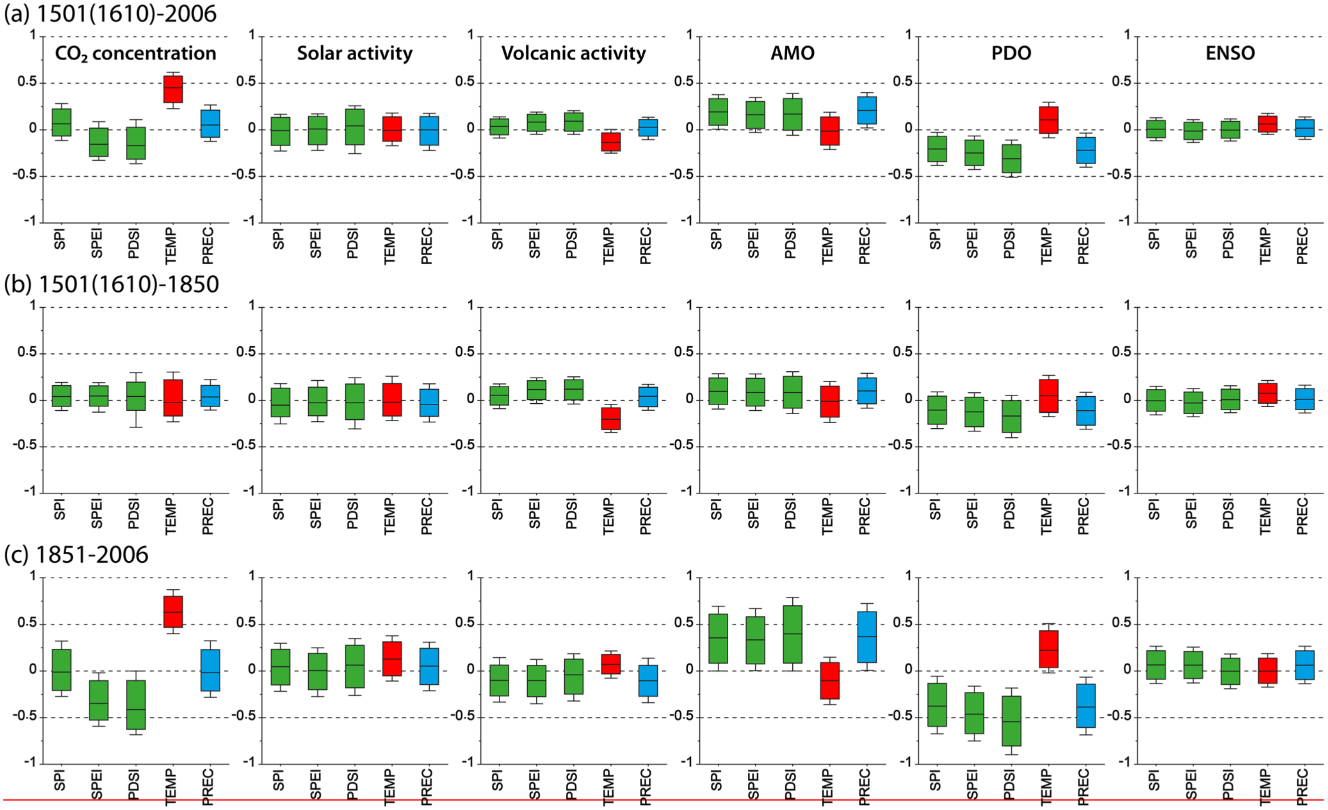


Figure 3. Fluctuations in reconstructed annual series of internal climate variability modes: (a) El Niño – Southern Oscillation (ENSO ~~index by Li et al. (2011); ENSO,~~), (b) Atlantic Multidecadal Oscillation (AMO~~ and~~), (c) Pacific Decadal Oscillation (PDO~~ indices derived from data by Mann et al. (2009), detrended by 70-year running mean of northern hemispheric temperatures); smoothed by 11-year running means (darker lines)~~, (d) North Atlantic Oscillation (NAO).


(a) 1501(1610)-2006
(b) 1501(1610)-1850
(c) 1851-2006
CO_2 concentration
Solar activity
Volcanic activity
AMO
PDO
ENSO
1
0.5
0
-0.5
-1
SPI
SPEI
PDSI
TEMP
PREC

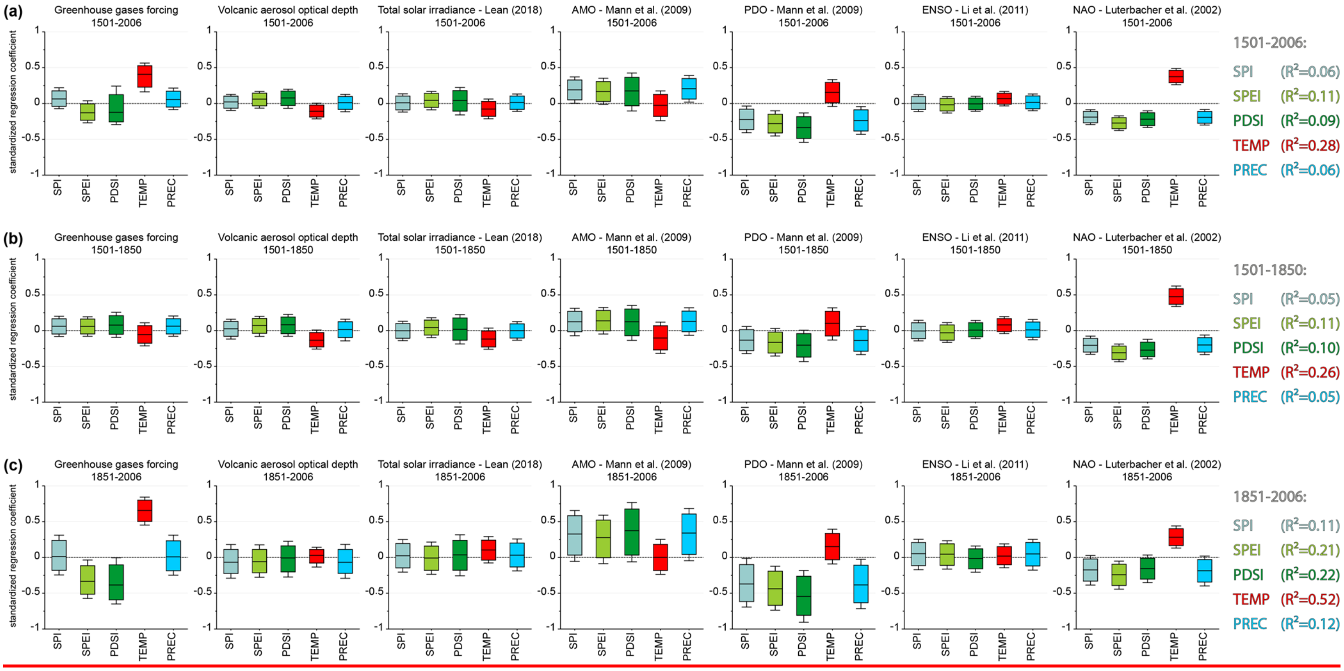
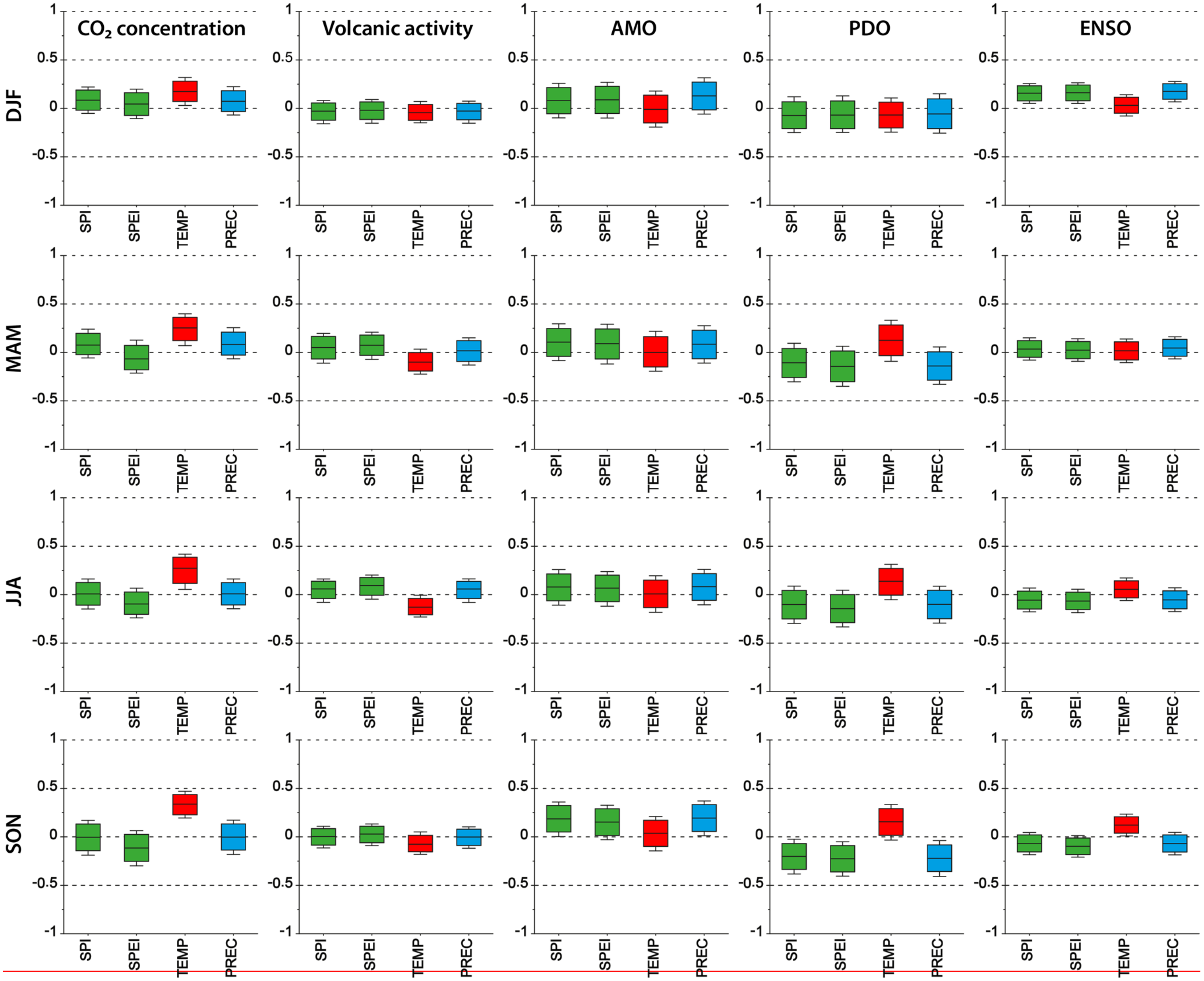

(a)
(b)
(c)
Greenhouse gases forcing
Volcanic aerosol optical depth
Total solar irradiance - Lean (2018)
AMO - Mann et al. (2009)
PDO - Mann et al. (2009)
ENSO - Li et al. (2011)
NAO - Luterbacher et al. (2002)
1501-2006
1501-1850
1851-2006
standardized regression coefficient
1
0.5
0
-0.5
-1
SPI
SPEI
PDSI
TEMP
PREC
1501-2006:
SPI (R^2=0.06)
SPEI (R^2=0.11)
PDSI (R^2=0.09)
TEMP (R^2=0.28)
PREC (R^2=0.06)
1501-1850:
SPI (R^2=0.05)
SPEI (R^2=0.11)
PDSI (R^2=0.10)
TEMP (R^2=0.26)
PREC (R^2=0.05)
1851-2006:
SPI (R^2=0.11)
SPEI (R^2=0.21)
PDSI (R^2=0.22)
TEMP (R^2=0.52)
PREC (R^2=0.12)

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,~~and 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. R^2: fraction of variance explained by the regression mapping.



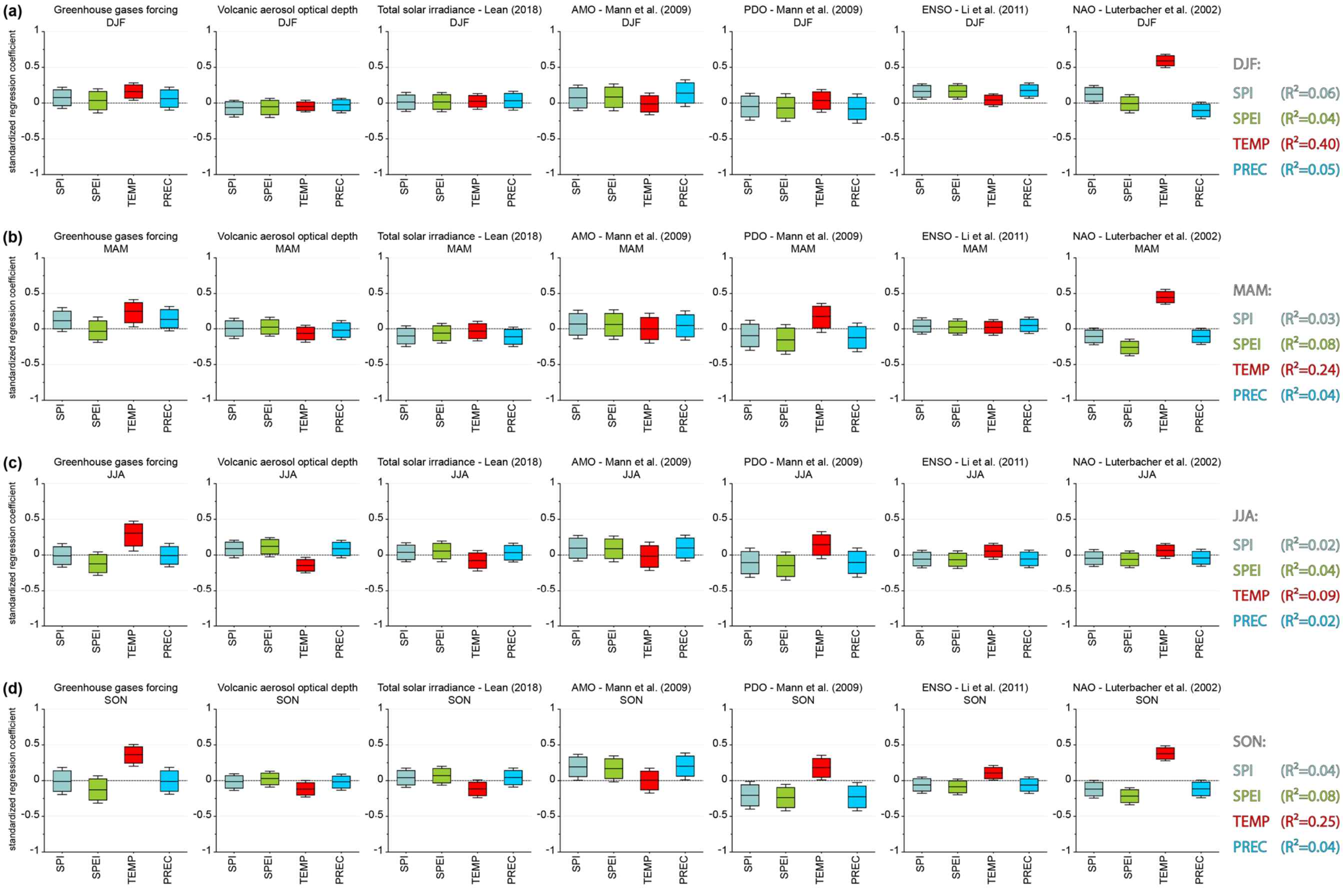
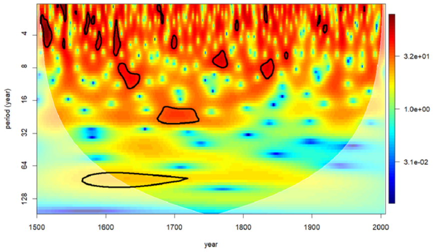
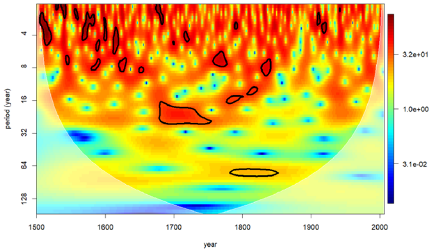


Figure 5. Standardized regression coefficients (central line, with 95% confidence interval shown as the box and 99% confidence interval as the whiskers), obtained by multiple linear regression between the predictands characterizing local Czech climate (drought indices~~—green~~, temperature ~~—red,~~and precipitation~~—blue~~) and a set of explanatory variables representing external forcings and large-scale internal climate variability modes~~; period 1501–2006, individual seasons~~ during individual seasons: (a) winter (DJF), (b) spring (MAM), (c) summer (JJA), (d) autumn (SON); 1501–2006 period. R^2: fraction of variance explained by the regression mapping.

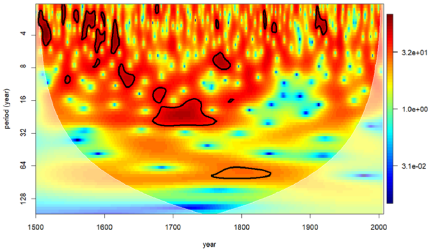
SPI



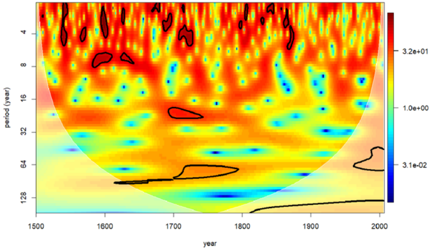
SPEI



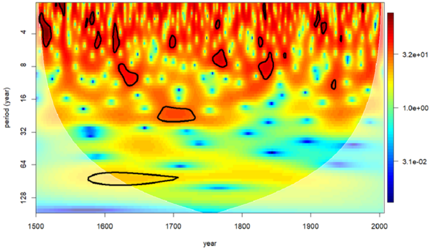
PDSI



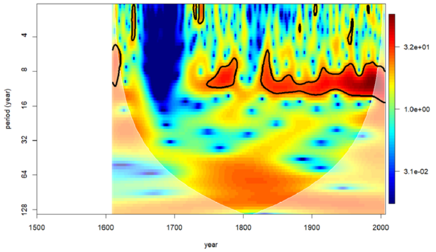
Temperature



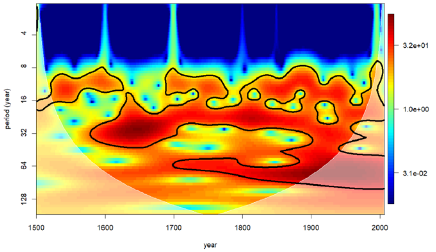
Precipitation



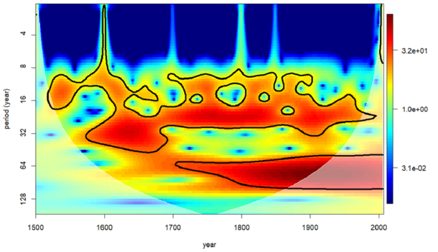
Solar irradiance



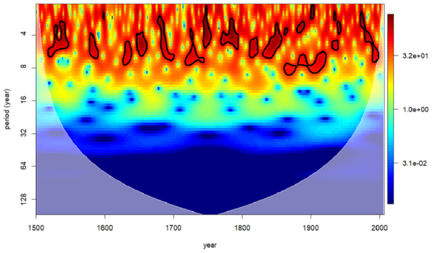
AMO (Mann et al., 2009)



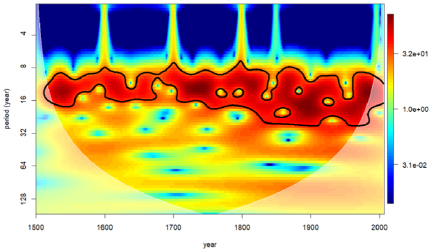
PDO (Mann et al., 2009)



ENSO (Li et al., 2011)



ENSO (Mann et al., 2009)



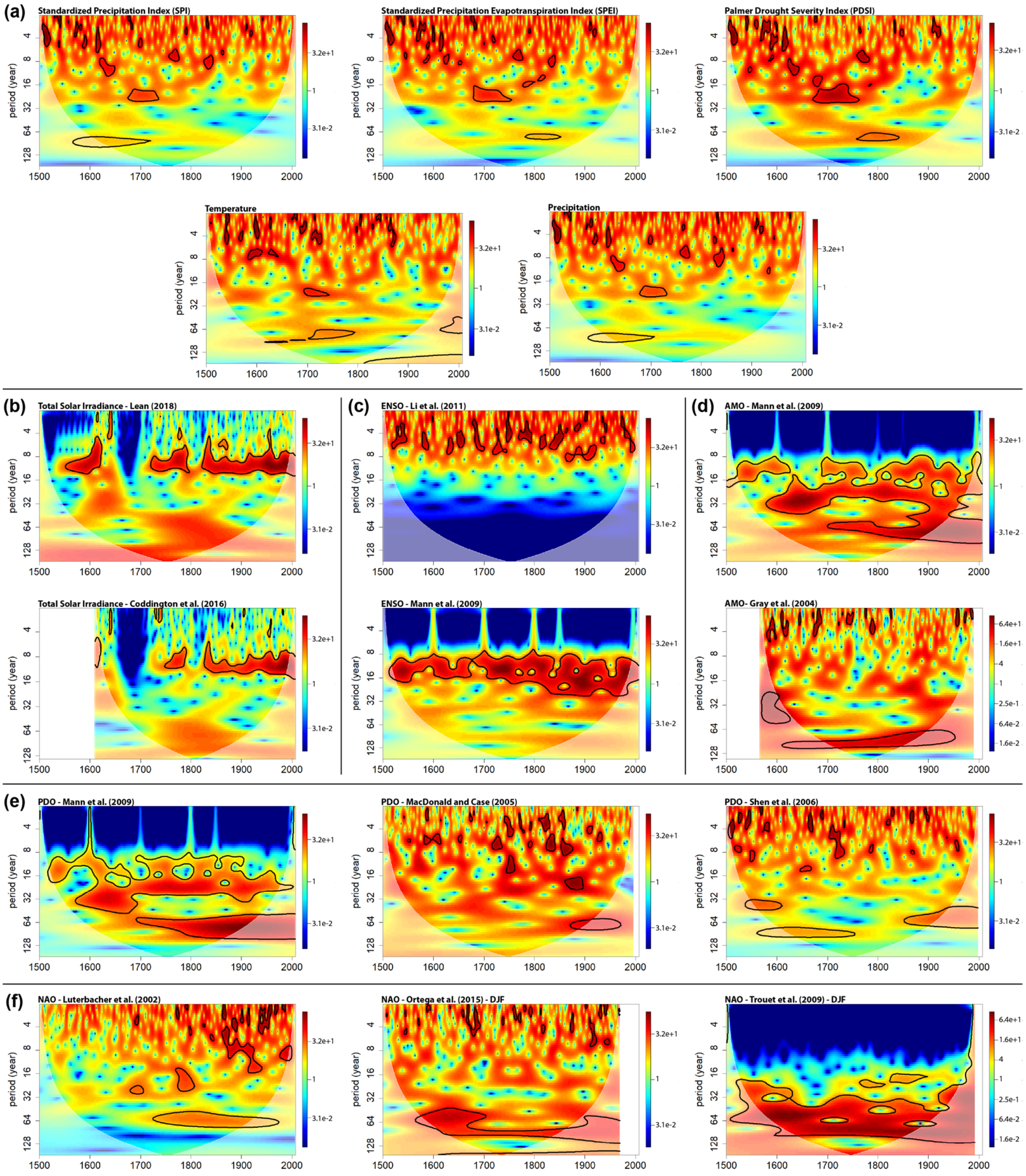
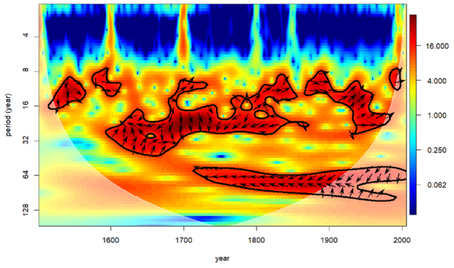
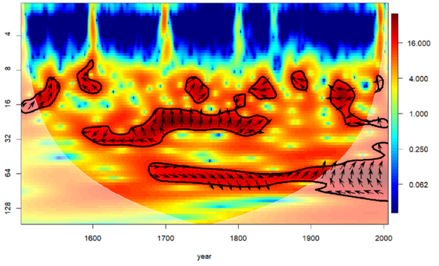


Figure 6. ~~Wavelet~~ Standardized wavelet power spectra of annual series of (a) Czech drought indices, temperature, precipitation, ~~and selected~~as well as of individual explanatory variables ~~(continuous wavelet transform, Morlet).~~with prominent oscillatory component: (b) total solar irradiance, (c) ENSO, (d) AMO, (e) PDO, (f) NAO. Areas enclosed by black line correspond to wavelet coefficients statistically significant at the 95% level, ~~AR1~~AR(1) process null hypothesis.

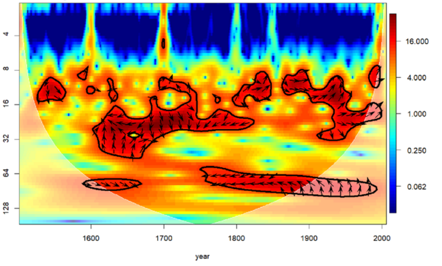
SPEI vs. AMO



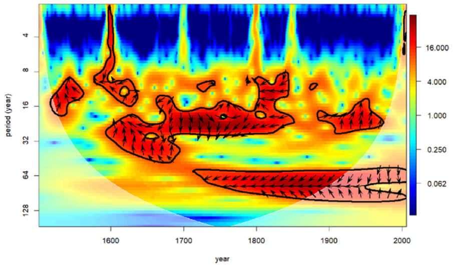
Temperature vs. AMO



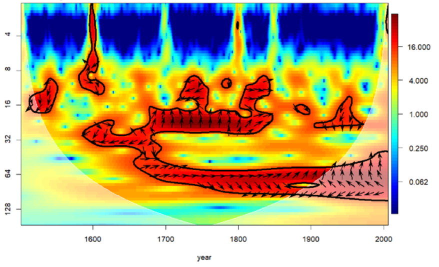
Precipitation vs. AMO



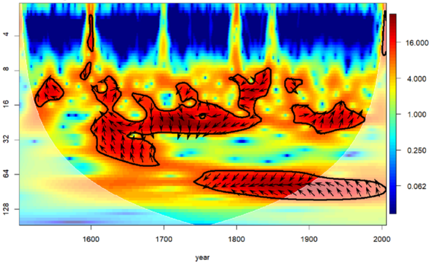
SPEI vs. PDO



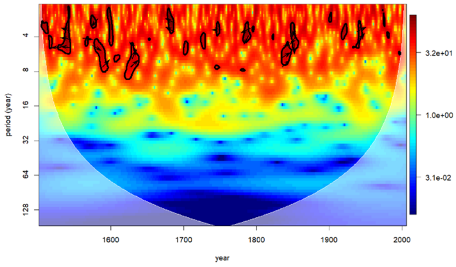
Temperature vs. PDO



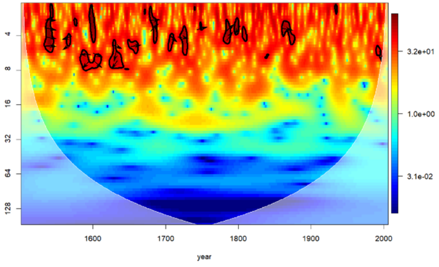
Precipitation vs. PDO



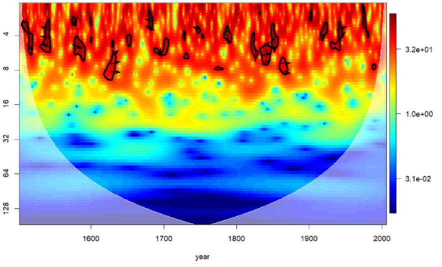
SPEI vs. ENSO (Li et al.)



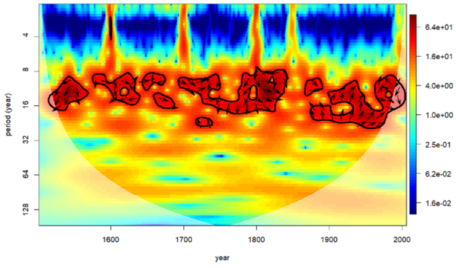
Temperature vs. ENSO (Li et al.)



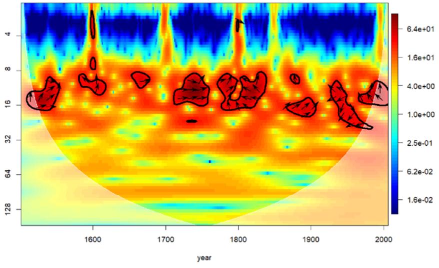
Precipitation vs. ENSO (Li et al.)



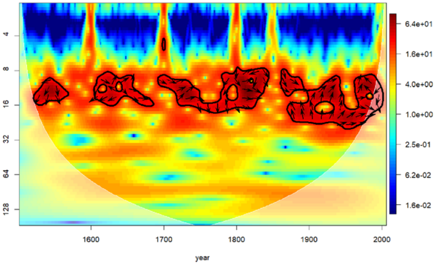
SPEI vs. ENSO (Mann et al.)



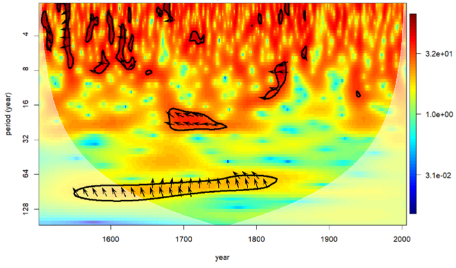
Temperature vs. ENSO (Mann et al.)



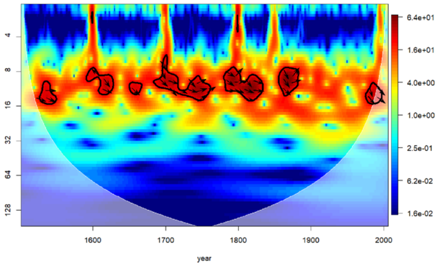
Precipitation vs. ENSO (Mann et al.)



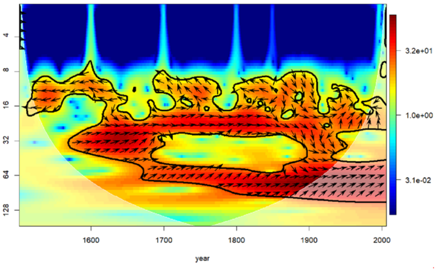
Temperature vs. Precipitation



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



AMO vs. PDO



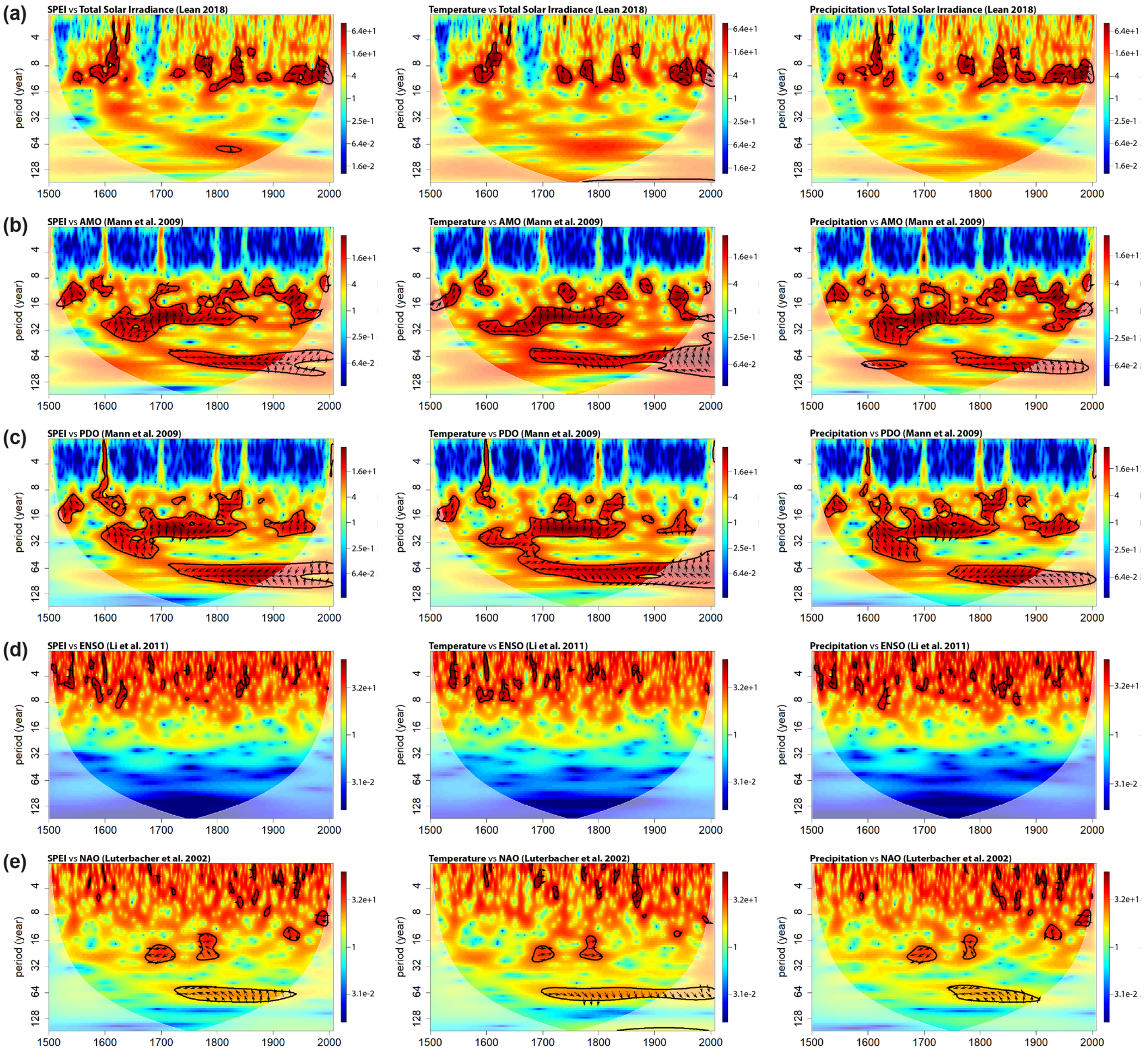


Figure 7. Standardized cross-wavelet spectra between series of Czech SPEI, ~~central European~~ temperature, ~~Czech~~ precipitation and selected explanatory variables with distinct oscillatory component: (a) total solar irradiance, (b) AMO, (c) PDO, (d) ENSO (e) NAO (annual time-step; standardized and bias corrected, as per Veleda et al., 2012). ~~Coherences~~Areas enclosed by black line correspond to cross-wavelet powers statistically significant at the 95% level~~ are enclosed by black line~~, AR(1) process null hypothesis; the arrows indicate local phase difference, with → corresponding to the two signals being in phase and ← indicating a shift of half the period.