We would like to thank both referees for their valuable comments regarding our manuscript. We tried to incorporate their suggestions into 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. In particular, there were several very relevant observations by reviewer #2 regarding interpretation and reliability of our results. We have tried to modify our presentation to address these; however, some of the suggested extensions of the analysis (such as incorporation of analysis more focused on the instrumental period) would result in substantial extensions our analysis, beyond its intended scope.

Please see below for individual comments of both referees, our responses and the corresponding changes to the manuscript.

REVIEWER 1

This is the revised version of a paper which I had reviewed earlier. The authors have done a thorough revision of the paper and have taken the main criticism into account. Their replies and iterations were done in a careful manner. Now the Discussion seems overly long - but I guess having asked for revisions, we now have to live with that. So I am happy with the revisions by the authors and have only very minor comments (e.g., Fisher -> Fischer, "borderline significant" -> perhaps better give p-value, conform -> confirm etc.; there are several more - please have another careful read).

Thank you - we re-read the manuscript and made a few corrections/changes, hopefully improving the text. With regard to the specific suggestions above:

- The spelling of 'Fischer' has been corrected.
- Confidence level is now given when 'borderline significant' results are mentioned; we would however prefer to preserve the term itself, to underscore results that were just at the edge of statistical significance (unfortunately we do not have p-values themselves calculated from our significance tests).
- The term 'conform' was used intentionally, not as a synonym/misspelling of 'confirm'

REVIEWER 2

Description

The paper addresses the identification and quantitative attribution of drought variability over the Czech lands in terms of three drought indices spanning over the last 5 centuries. It targets drought-climate links comparing drought indices with climate (temperature and precipitation) reconstructions, modes of internal variability and external forcing parameters.

As I stated in my first revision, I think the purpose of the paper has value and steps in the attribution of drought variability over the Czech Lands or progress in understanding mechanisms would be valuable in my view to support publication. The revised version of the manuscript includes new analysis like NAO related links and other aspects not considered in the initial version. It also considers more reconstructions of specific indices and provides a more clear view of the difficulties to relate, at least with this technique, the variability in external forcings and large scale climate drivers with Czech drought during the last few centuries. I think the authors have made an effort to provide a more clear manuscript and the discussion of their results is fair and honest in declaring the understanding that can derive from this analysis and its limitations. I think that there are still a number of issues that have to be taken care of. In general I would say that individually taken they are not major but there is a number of them. I will leave it to the consideration of the Editor whether a new revision cycle will be needed.

General comments.

GC 1. Overall I would invite the authors to really think about what we gain from this analysis and have clear statements about the confidence and reliability of the links they report on, and report on this assessment in the conclusions as a take-home message for the reader. Some of the resulting coefficients and relationships stem from the (sometimes clearly, sometimes marginally clear) analysis of some of the reconstructions and not from the others. I think the authors do an honest job in highlighting this (and some of my subsequent comments go in this direction), although I would suggest really making an effort for a very clear assessment of how much confidence we can have on these results.

I think it is important to minimize the danger that results are cherry picked in the future using this manuscript as a reference for clear links between a mode of circulation (say PDO or AMO) and drought when in fact, it is not, and the relationship may be very much dependent on the reconstruction considered. I think this is particularly the case when the study provides coefficients resulting from a multiple regression analysis that considers data in different periods but there is no insight about the mechanisms that may support such relationships. Perhaps a message that needs to be clearly stated is that there is too much uncertainty and that even if one technique may provide relatively clear results in depicting some level of relationship (very small R^2) between drought and large scale drivers and forcings, there is too much uncertainty for having confidence on the purported relationships as other reconstructions do not provide that clear link.

> We agree that there are still questions not resolved by our analysis, as well as uncertainties and interpretational caveats that should be clearly communicated to the reader. While we have already tried to highlight them in the previous iteration of the

manuscript, we have now further extended and restated some formulations (especially) in the Results, Discussion and Conclusions sections, to emphasize the potential problems even more clearly, and to better match our interpretation to the results shown. This was done in a large part in response to individual comments and suggestions of the reviewer - please see the points below for specific details.

GC2 Would the authors have arguments to believe that any specific reconstruction from the ones considered for ENSO, PDO, AMO or NAO is better or more reliable than the others? If so, this should be clearly stated. It is actually done so to some level. At a first stage the reconstructions are considered alike to derive relationships to regional drought and then the relationships are used to decide that one reconstruction is more trustworthy or reliable or better than the other because it shows a more intense relationship with drought. I think this is a dangerous path. Indeed the manuscript steps onto this ground and I would strongly suggest revising these types of arguments. After all I think that if this manuscript gets to publication, its value for the community should reside as much in the quality of the arguments as in the strength of the statistical results.

The problem of reliability of individual reconstructions is certainly an important one, but one difficult to resolve. There are indeed substantial contrasts between our predictors: in particular, the three PDO-approximating signals are almost uncorrelated, sometimes actually slightly anti-correlated (with Mann et al. and MacDonald&Case series correlated at r = -0.17). We do not dare to explicitly mark any of the reconstructions as inherently "more trustworthy or reliable", as such assessment would have to be backed by a deeper analysis of the source proxies and their processing. It would perhaps be possible to argue that a multi-proxy reconstruction (such as the one by Mann et al. 2009) might be superior in general reliability to reconstructions based on specific data from a particular region. Then again, perhaps individual reconstructions should be treated as reflections of different aspects of the systems studied (and therefore not completely mutually interchangeable, with each of them potentially suitable for a different purpose). Ultimately, to resolve the question which (if any) of the reconstructions should be considered superior would require a separate (and quite sizable) analysis of its own.

To communicate the above more clearly in our paper, we changed the formulation in the part of the Discussion dealing with PDO and differences between its individual representation (paragraph at p. 15, l. 12+). Please note that while we do present results for the 'best fitting' reconstruction (i.e. Mann et al. data for AMO/PDO) as a part of our core results, the results for the alternative versions of the predictors are also given (even though sometimes in a reduced form, as the amount of illustrations would have to be substantially increased otherwise). The differences and uncertainties are mentioned and discussed, especially in various parts of Discussion and Conclusions.

GC3 A great deal of the material of the manuscript at this stage refers to the Supplementary Material. Actually there are more plots in the SM than in the main document. Much of the discussion part relies on this bulk of material. I really wonder if some of the results should not be promoted to the main text.

Figs. S1 and S8 have now been moved to the main manuscript as Figs. 6 and 9, respectively. We would prefer to leave the rest of the extra materials in the Supplement, as they are either related to variables showing just limited influence in our analysis, or they are not essential to our key messages (and the main text has already grown rather considerably compared to our original concept).

Specific comments

SC1 Section 2.1.

Various indices to characterize drought at seasonal and annual timescales are used in the paper and introduced here. The last paragraph indicates that these indices are derived in Brázdil et al (2016a). The first paragraphs of Sec 2.1 indicate the differences in the predictor variables that lead to different definitions of SPI, SPEI and PDSI. I suggest that it may be good to include here some sentences of the different information that using these three indices instead of a single one can provide in the light not only of a priori definitions but also of the results in Brázdil et al (2016a) or on what may be expected to obtain later on. This information may be of interest for the reader to have some understanding of the interpretation of the indices for this specific area based on previous experience of the authors. Are the indices very different? Do any of the three reflect any specific features? Indeed the low frequency variability in fig 1 looks very similar for the three of them. I suggest providing the correlations between each pair of the three indices available. This will allow the reader for knowing two what extent having 3 series instead of one adds information. Otherwise the reader misses some, probably justified, rationale for this set up.

We have added the values of mutual correlations in the text, along with a brief a rationale for using three indices rather than a single one (end of Sect. 2.1):

"Note also that despite the profound similarity in temporal variations of individual drought indices, manifesting in their strong mutual correlation (Pearson correlation coefficient $r = 0.93$ for the annual values of SPI-SPEI, $r = 0.83$ for SPI-PDSI, $r = 0.88$ for SPEI-PDSI over the 1501-2006 period), each of them emphasizes different aspects of meteorological droughts, be they simple precipitation sums captured by SPI, evapotranspiration variations considered by SPEI, or longer-term soil moisture status embodied by PDSI. Hereinafter, results for multiple indices are therefore presented and discussed, with regard to their common features as well as mutual contrasts."

Regarding the details on differences in their definitions: please note that a brief version of this information is provided when introducing the drought indices in Sect. 2.2, along with links to more exhaustive sources. When relevant, contrasts between outcomes stemming from use of different indices are also highlighted in the Results and Discussion sections (for instance, when the behavior of SPI (a purely precipitation-based index) differs from the behavior of SPEI/PDSI (indices considering temperature in addition to precipitation)).

SC2 Section 2.2. Page 5, Line 15-17. '…extended back to AD 1501 using CO_2, CH_4… concentrations obtained…' Who did this extension? If obtained by the authors indicate reference. If developed by the authors, please, explain how. The reference to the web is perhaps better in the figure caption? A preferable alternative is always a reference.

Approximate formulas from IPCC (2001) were used for the extension of the radiative forcing series; this is now mentioned in Sect. 2.2.

The web link points to an online data archive; we are not aware of a matching traditional reference.

SC3 Section 2.2. Page 5, Line 15-17
Why wouldn't aerosols also be considered? This is an important anthropogenic component. The authors have discussed this in the response to the previous review. Please consider arguing here why including aerosols and LULC is not worth.

Please note that we mention the effects of possible inclusion of (globally averaged) aerosol forcing at the end of the first paragraph of Sect. 4.1:
"It is also worthy of note that, due to very strong correlation between the respective time series, very similar results would have been obtained if the GHG forcing series was replaced with a predictor representing just CO2-related effects, or by total anthropogenic forcing including the effects of man-made aerosols."
This explanation states that within the scope of our methodology, almost no change would result from using aerosol-inclusive anthropogenic forcing; we do not dispute their physical relevance, but since their inclusion would not change our results, we do not include discussion of possible aerosol effects either.

As for the LULC data, we do not use or mention them, primarily due to non-existence of a usable (homogeneous, representative, and five-centuries-long) reconstruction of a time series quantifying LULC changes.

SC4 Figure 1
o Figure caption: suggest changing 'Fluctuations in the annual series of…' by 'Annual series of…'

Changed.

o References: they are clearly exposed in the legends. I would rather suggest having them in the caption, but this is not critical. The Meinshausen one, extended… a note on this can better be incorporated to the caption, as any other feature related to the construction of the figure or source of data.

In this case, we would prefer to leave the references directly in the figures rather than in their captions, since names of the author(s) of the relevant publications serve as the only identifiers of different reconstructions of the explanatory variables, and they are used as such everywhere else in the manuscript. The method of extending the GHG forcing data is given in the respective part of Sect. 2.2 (second paragraph), we would prefer to not duplicate it in the figure caption.

o Scale: the volcanic forcing should be negative. Units would be more clearly stated in the axis labels than in the legends.

Please note that the data in Fig. 2 (as well as the time series used in our analysis) represent stratospheric aerosol optical depth (and thus non-negative values), not forcing as such.

As for the units placement, we would prefer to keep them as a part of the horizontal subtitles (it seems more consistent graphically, considering that the drought indices are dimensionless and unit is thus not given).

SC5 Figure 2

o Figure caption: suggest changing 'Fluctuations in reconstructed series of…' by 'Reconstructed series of…'

Changed.

o The Luterbacher et al (2002) series looks strangely flat. Can the authors please check on that one? Previous representations of this series show more low frequency variability. The resolution of the plotted series is not indicated and is confusing after reading the text (monthly, seasonal, annual… see MC7.

As far as we can tell, the series is consistent with its representation in the source paper by Luterbacher et al. (2002) – please see Fig. R1 below (DJF season, since only winter data are visualized in the original 2002 paper).

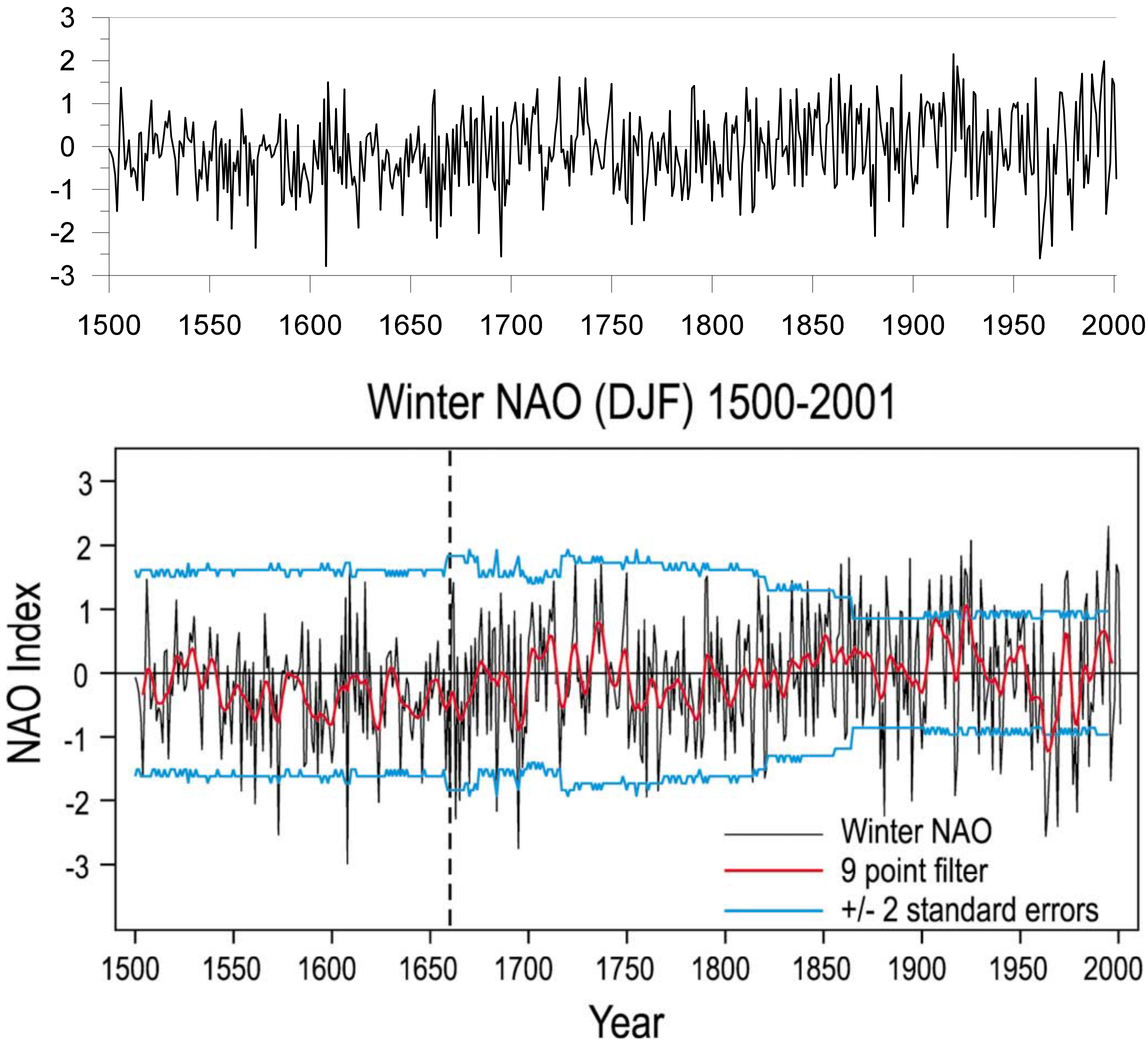


Figure R1: (top) DJF NAO index used in our analysis, derived from Luterbacher et al. (2002) data, (bottom) the original graph of the same series as presented by Luterbacher et al. (2002, Fig. 3).

o Any technical details in the construction of the series added by the authors like filtering low frequency components by subtraction in the Mann et al series can, for the sake of clarity, be mentioned in the caption or a note to the main text be made.

The detrending procedure is described in Sect. 2.2, when introducing the ENSO/AMO/PDO series; we would prefer to not repeat its description in the figure caption.

o The reconstruction of Mann et al (2009) and MacDonald and Case (2005) seem to be in phase opposition. Maybe the authors should consider commenting on this in the main text as it can have implications for the subsequent analysis.

Indeed, the correlation between the two series is negative, albeit relatively weak (-0.17 for the series of annual values), which is still rather underwhelming value for indices supposedly pertaining to the variability of the same climate oscillatory system. We have added a note of this fact to the Discussion, to complement the previous remarks pointing to the uncertainties stemming from contrasts between individual reconstructions. However, as also discussed for GC2/SC7, more detailed analysis of the reasons for these differences is beyond the scope of our paper, as it would require a detailed assessment of the data and methodology involved in preparation of each reconstruction.

SC6 Figure 6
o In the logics of the text, this should rather be Figure 4.

Our intention was to keep the wavelet and cross-wavelet illustrations close to each other, and close to the discussion of the wavelet-related results in Sect. 4.2. The reference to Fig. 6 in the Data section is only minor and we would therefore prefer to keep the wavelet charts as Fig. 6 (Fig. 7 in the current revised version).

o Please check on the Luterbacher NAO index wavelet (see SC5).

While the wavelet analysis is able to separate oscillations pertaining to different parts of the time-frequency space, their statistical significance is subject to the overall properties of the time series (in this case to the structure of the corresponding AR(1) model, upon which testing of statistical significance is based). For this reason, statistical significance of some portions of the wavelet spectra may be lower than it would be for a smoother signal, less dominated by high-frequency components.

o Consider making a technical short note on the cone of influence in the caption. Also for the subsequent cross-wavelet plots.

Done: Figs. 7 & 8 captions have been extended with: "The lower-contrast areas pertain to the cone of influence, i.e. region with diminished representativeness of the wavelet spectra due to edge effects. ".

o The numbers and labels in this figure are too small. Check size of characters also in subsequent plots.

The font for sub-titles and color scale has been enlarged in all figures containing wavelet and cross-wavelet spectra.

SC7 Section 4.1, page 8.
● Line 24-25. 'A statistically significant solar related signal was also absent in all individual seasons except for SOM' Right, and also additionally a somewhat marginal link in JJA, however they are negative! I suggest being really careful with these things. Otherwise statistical links are

highlighted but they may have little physical basis. What can be the reason for a negative relationship of temperature with solar variability?

> The problem here might lie with the 1501-1609 part of the Lean (2018) data, which is reconstructed in a different manner than the 1610+ part (for which sunspot data were employed, and which can thus arguably be considered more reliable). For this reason, we also included analysis results covering the 1610-2006 period only (Figs. 6d, 6e) – these show solar-related coefficients to be closer to zero and far from statistical significance, albeit still negative (which is likely just an effect of sample variance, not indication of actual cooling). We reordered the text in Sect. 4.1, 2nd paragraph, to make the reasoning for our claim of solar non-relevance more clear.

● Regarding ENSO, AMO and PDO. It would be good if some mechanistic explanation, linking to other literature, can be provided to support the confidence on these correlations. For instance the positive correlations with wetter DJF or drier SOM… It is desirable to provide some support for these relationships on the basis of mechanisms and/or similar relationships in other studies.
The same applies for the wetter DJF and SOM AMO situations or the influence of the PDO to dry conditions. In this last one, why would PDSI be more sensitive according to the experience of the authors? Regarding the PDO, I would be interested in having some assessment by the authors on the confidence on these results, since a) the relation is found only with the Mann et al data, and b) this reconstruction seems to have a very different behavior to Macdonal and Case and Shen, sometimes in phase opposition.
Finally, according to Fig 4 and 5, the influence of the PDO seems to be the largest. It is important to have some assessment on confidence on these results on the basis of previous literature and the results herein, as a) these results rely only on one reconstruction and b) the resulting coefficients are even larger than the NAO. Would the authors then support a larger influence of Pacific variability on Czech drought than that of the North Atlantic? When reading subsequent parts of the text this is not the case, but the numbers play in this direction at this stage and some comments on this may be advisable.

> As also discussed in relation to GC2: While it would certainly be beneficial to expand the explanation of the mechanisms behind the formal links pointed out by our analysis, our options are limited. In the absence of a dataset covering our five-centuries-long analysis period and allowing for investigation of the circulation patterns (such as a reanalysis), it is difficult to ascertain/validate the nature of the teleconnections. As for comparison with pre-existing studies, there seems to be a great deal of disparity between the character of the explanatory variables we used and the (largely observational) data employed in comparably focused studies (specifically, for PDO, the Mann et al. data provide long series, but virtually devoid of shorter-term variability, contrasting with the usually employed observational PDO indices, relatively rich in inter-annual (and sometimes even inter-monthly) variations). As a result, different time scales and processes likely play role in establishing the relevant teleconnections, making them difficult to compare between our study and the others.

To give a specific example: Baek et al. (2017; doi: 10.1175/JCLI-D-16-0766.1) performed a correlation analysis of PDSI with regard to various climate variability modes, including PDO. They identified a relatively large positive correlation between PDO index and PDSI in Europe – a result formally opposite to ours in terms of the correlation sign. On closer inspection, there appears to be an anticorrelation between Mann et al. PDO temperatures and the JISAO PDO index used by Baek et al. (http://research.jisao.washington.edu/pdo/PDO.latest.txt), valued at r = -0.37 for the JISAO index smoothed by 11-year moving average (note that this difference does not arise from our pre-processing of the Mann et al. data, although the anti-correlation becomes somewhat stronger after the detrending). This raises a question of definition and calibration of individual signals (including perhaps their sign when PCA is involved in the index definition) – an issue that would require a deep analysis of various definitions and/or reconstruction approaches for the explanatory variables, probably sizable enough to warrant a separate study. Only after this, results of the attribution-based studies could be meaningfully compared.

As for the weaker-than-expected influence of NAO, it can arguably be explained by annual averaging, at least partly - please see our response to SC14. (note also that NAO's influence in Czech precipitation – the key factor shaping all the drought indices – is smaller in the Czech Republic (CR) than it is in some other parts of Europe, due to CR's geographic position near the transition from positive to negative precipitation-to-NAO response.)

SC8 Fig. 4 and 5

R^2: The explained variances shown through Fig 4,5 seem to be very weak in general. This means the bulk of drought variability is not explained by these indices. Perhaps the fraction of low frequency variability explained is larger?

Perhaps it would be advisable to do the same exercise on purely instrumental indices (ENSO, PDO, AMO and NAO), not reconstructions and have that as a benchmark of what should be expected in the frame of the reconstructions. This should be viable in terms of assessing interanual variability in the instrumental period and would place a more realistic perspective on the level of expectations we can have on the reconstructions. After all, most of the variability the study is addressing is interannual to multi-decadal, well represented in the instrumental period.

Indeed, if only low-frequency variability was considered (e.g. after both the target and explanatory variables have been smoothed by a moving-average filter), the fraction of variance explained would be higher. However, such an approach would not allow to directly consider the faster-variable explanatory variables (episodic volcanism, 11-year cycle in the solar forcing or sub-decadal variations in the climate indices). Since our aim was not to construct a predictive model (and thus explain as much variability as possible), but rather to identify factors with potentially relevant links to our target variables, our interpretation is not centered around R^2 values, but is based on values and statistical significance of the regression coefficients.

SC9 Section 4.2

● In general I agree with the description of Section 4.2. I have reservations regarding talking about periodicities. Talking about periods or frequencies in a wavelet or spectrum is fine, but I would suggest avoiding conveying the message of stable periods/cycles. Otherwise, prediction based on cyclic memory would be possible. I would rather talk about timescales of variability. Having said that, I leave that to the criteria/taste of the authors.

> The reviewer is correct to point out that stable periodicities would be an indication of simple, straightforward predictability, something our analysis does not support. However, note please that whenever a stable periodicity is mentioned in our text, the formulation actually points to its absence, not presence.

● The sentence in page 11 ' No significant match between the oscillations in the NAO index series and the drought indices was found … (it is worthy of note that this result does not imply a lack of relationship as such, merely an abscense of common periodicities…' I would disagree with this statement. If there is a relationship (linear) it must be appreciated in the covariability shown by crosswavelet or crosspectra. Perhaps I misunderstood the statement, but please, reconsider it, since this can be a very misleading one.

> Please note that the lowest period detectable by the (cross-)wavelet analysis corresponds to twice the sampling time, i.e. 2 years (the Nyquist frequency). Much of the variability of the NAO index happens on year-to-year basis, and the high-frequency component can almost be considered white noise (lag-1-year autocorrelation of the NAO series is just 0.07). As a result, this variability (as well as the respective links to the drought indices/temperature/precipitation) is not captured in the cross-wavelet spectra, even in the presence of a clear linear relationship between the series. (please see also our response to MC9)

SC10

Section 5, page 12. Lines >2. 'Even so it should be emphasized that regression … does only reveal formal similarities… . This is particularly true in the case of signals dominated by simple trends, such as the gradual rise of GHG radiative forcing… Our results should be considered a supportive argument regarding the relationship between the drought regime and the anthropogenic forcing, not a definitive proof of the causal link.'

Page 17, line 7: 'GHGs concentration … matches the long-term trend component in the temperature sensitive drought indices quite well… Even considering that statistical attribution analysis can only reveal formal similarities… the relationship during pre-instrumental and instrumental periods and other available evidence… support the existence of an anthropogenic induced drying effect in central Europe…'

Please check the consistency of the level of reassurance of these statements with the results of the paper. The coefficients in Figs 4 and 5 somewhat support the role of GHGs, mostly in the industrial period for SPEI and PDSI and for temperature in the whole period. Seasonally, temperature is clearly positive and SPEI shows some negative response in JJA and SON. However: are temperature and SPEI and PDSI trends significant themselves? See Figure 1. Temperature trends seem to stand out of the background envelope of variability, but I would not be able to ascertain this is the case for SPEI and PDSI. Please think how to formulate attributing statistical relationships to trends that …may not be significant? First ascertain they are (detection) and then try going further.

> In this case, our evaluation of the GHG-related components in the drought indices is based on the role of temperature in addition to the formal (non-)significance of individual coefficients themselves. In other words, a positive significant response in temperature is considered a justification for considering the negative response in temperature-sensitive indices (SPEI, PDSI) to be relevant and interpretable, even at $p > 0.05$. We modified the related formulations somewhat (especially in the Conclusions), to better convey our reasoning.

SC11

Section 5, page 13. Lines >5. 'While previous studies… of explosive volcanism this analysis of more than five centuries of data has revealed a more distinct volcanic imprint suggesting a tendency to wetter conditions following major eruptions… most prominent in summer.' Consider also page 8 line 31: 'The volcanism effect … precipitation is non significant… As a result the volcanism-attributed component is negligible in precipitation-only SPI, but somewhat more prominent (even still non significant) in temperature sensitive SPEI and PDSI. The season specific… during summer, when a borderline statistically significant response also appears for precipitation and both SPI and SPEI.

Page 17, line13: 'A distinct signature of temporarily wetter conditions following major … eruptions…was detected.'

These statements suggest different levels of reassurance of the relationship to volcanic activity. I think the 'distinct signature' statements overstate the relationships found with drought indices. In Fig. 4 none of the drought indices or the precipitation show coefficients that significantly stand out of 0. In Fig. 5 this is also the case except for summer when SPEI, SPI and precipitation tend to show values larger than 0… but can we call that a 'distinct signature'? Please evaluate the level of confidence on the relationships found and make sure the statements are really supported by the data and the relationships found. This applies also in general to other statements of the manuscript. See also next comment.

> Again, our interpretation reflects the relatively clear volcanic signal in temperature as a justification for considering the components in the temperature-sensitive drought indices (SPEI, PDSI) more physically meaningful, even when statistically non-significant. It is true, however, that the formulation regarding the drought indices may have been overly strong: in the revised version, 'a distinct signature' was changed to 'a signature', plus some other minor changes have been made to the related statements.

SC12

Regarding the volcanic response. The authors report that a lagged analysis bears no clear results. This is not strange in terms of covariance/correlations. A more appropriate analysis can be a simple epoch analysis in which the authors would synchronize the most important volcanic events in the last few centuries and the corresponding values of drought indices, temperature and precipitation. I think this would be a meaningful complementary plot to the ones shown here and would fit well to the discussion. In the summer it may show a clearer signal even.

> One problem with simple epoch analysis is the lack of information about intensity and interaction of individual eruptions, as they are treated as simple yes/no events. Our analysis primarily suggests a presence of volcanic effects for the temperature series and, in turn, for the temperature-sensitive SPEI and PDSI series (albeit not always in a statistically significant form). Since the analysis of European temperature data over a period quite similar to ours was already done by Fischer et al. (2007), and they reported results rather consistent with ours (summer temperature drop following major volcanic eruptions), we prefer to reference this study instead of implementing the epoch analysis ourselves.

SC13

Section 5. The discussion in pages 14 to 16 is well organized regarding the structure and the use of literature. I quite like that. There are however, two additional features that I find odd and would advise differently.

a) One is the systematic use of supplementary material. A considerable bulk of supporting evidence relies on it. It can be a matter of style but having more figures in the SM than in the main text and these figures being so relevant for the interpretation of results suggests to me that some of these figures should be included in the main document.

> As also discussed for GC3: Figs. S1 and S8 have now been moved to the main manuscript as Figs. 6 and 9, respectively.

b) There is an issue with the interpretation and discussion of different reconstructions and how they provide or not evidence for variability of regional drought. One specific case is that of the AMO PDO indices and their differences. I understand this is somewhat an evolution of the PCA analysis in the first version of the manuscript. I would not say it is wrong, but as it is presented it reads like playing with numbers. The other reconstructions do not support that and all of a sudden the differences between two specific reconstructions of the same type (that have already been through a considerable filtering process) renders some correlations. It is hard to have confidence on these results and bear they are really representing some differences between Atlantic and Pacific variability. I think overstating those numbers is dangerous. This results permeates to the conclusions, with cautious phrasing, that is true… but I do not think there is good ground for it if it is not supported by some serious rationale based on literature or mechanism based arguments. How can the authors provide some confidence that these are not numbers obtained just by chance?

Our inclusion of the common AMO/PDO component and of their difference was motivated by the strong collinearity of the PDO a AMO signals (which, by the way, was even stronger before the respective series were detrended, due to their shared long-term component – see Fig. 1 in Mann et al. 2009). Because of this strong correlation between the AMO and PDO series, linear regression cannot reliably distinguish between their influences; using PCA (or, in this case, its primitive 'mean vs. difference' interpretation) allows for a better defined setup of regressors. Since we found it interesting that the AMO-PDO difference constitutes a more influential predictor, despite it being responsible for just a small fraction of the combined variance in the original AMO/PDO pair, we mentioned this outcome. Note, please, that we avoided an explicit interpretation of this results as a proof an actual link between AMO-PDO contrast and our target variables and stressed a need for future validation (Conclusions, point (iii)). We have now also slightly modified the respective sections of the text to make this even more clear.

SC14

Section 5. Page 15, Lines > 21. See also SC8. '… this role appears to be played by interannual variations associated with weather changes closer to synoptic time scales and tied to local climate…'

Still, it is strange that only NAO would not for instance account for a larger percentage of variability. And if there are other (European) local modes that account for more variability, shouldn't these actually the ones that should be considered then in this analysis?

I would advocate for having a benchmark of correlations with instrumental period indices that would then support to look at the indices selected in longer timescales.

The seemingly less-than-expected dominance of NAO likely stems from several factors. First, while there are profound inter-annual variations in the NAO index series, a substantial part of its variability (and thus influence on local climate) takes place at sub-annual time scales; the annual averaging therefore somewhat diminishes NAO's relative prominence. Furthermore, annual averaging also aggregates strong NAO influence in winter with its weaker effects in other seasons. Note, please, that the NAO influence is more pronounced in the DJF season (Fig. 5a) in the temperature series (due to tighter temporal focus, as well as winter conditions being more affected by NAO than the rest of the year). (You may also notice almost non-existent effect of NAO on SPEI in winter, despite its links to both temperature and precipitation – this seems to be due to substantial positive correlation between central European winter temperature and precipitation, the influences of which effectively cancel-out each other in the SPEI series.)

Regarding other potentially influential variability modes (such as Eastern Atlantic / Western Russia Pattern or local central European circulation indices): while they are certainly something to be considered in a analysis focusing on recent climate variability, their usability for our study is constrained by the lack of reconstructions pre-dating the instrumental era.

As for extending our analysis to the instrumental-era inputs: This would shift our intended focus substantially, and would require introduction of multiple additional datasets, as well as major additions to the methodology applied (e.g., adding circulation patterns analysis, unfeasible and thus unused for our five-centuries-long-period, but possible and desirable for recent records). While we would prefer to not do this in the present study, we are currently preparing a follow-up analysis specifically targeting the possible links and teleconnection for just the 20th and 21st centuries, in a wider geographical and physical perspective.

Minor comments

MC1 Section 2.2, page 5, line 9: '…with notable oscillatory components in Fig 6. This is the first time Fig 6 is mentioned. The second in Page 6, Line 8. The previous figure to be cited is Fig 3. I think that the logical sequence of the text asks for moving Fig. 6 to the 4th position. This would make a more logical flow in the text.

As also discussed with regard to comment SC6: Numbering of the figures was chosen to keep illustrations with wavelet and cross-wavelet spectra close to each other and to the sections discussing them.

MC2 Section 2.2, page 5, line 9: '…with notable oscillatory components in Fig 6.' Why 'with notable oscillatory components'?. Better indicate why wavelet spectra are used… for actually all series.

This formulation is merely meant to emphasize that wavelet analysis was only applied to signals with oscillatory behavior consistent with variability in the wavelets employed (Morlet), i.e. not to trend-dominated series (anthropogenic forcing) or to series reflecting aperiodic time-asymmetric episodic events (volcanic activity).

MC3 Section 2.2, page 5, line 18. 'Variations in solar activity typically leave no clear imprint on the climatic conditions of the lower stratosphere' Check consistency with detection/attribution chapter in IPCC 2013.

The sentence was meant to convey the lack of distinct solar-related components reported by most comparable previous studies involving time series analysis (though it may also be mentioned that even the solar signal reported by the IPCC (2013) report is quite weak, and the respective aggregate confidence interval starts at zero for solar-induced temperature change since the pre-industrial period). Formulation in our manuscript has been revised to: "While variations in solar activity typically leave no or just weak imprint in lower tropospheric observational time series during the instrumental era..."

MC4 Section 2.2, page 5, line 24. 'The effects of major volcanic eruptions … but exhibiting just inconclusive local imprints during the instrumental period'
Really?. To what area does this statement refer to? Please, check consistency with detection/attribution chapter in IPCC 2013.

Similarly to our statement regarding the solar activity above, this formulation was meant to emphasize difficulty of reliably extracting the imprint of volcanic activity from the (relatively short) time-series covering the instrumental period. The sentence has now been slightly changed to: "... but exhibiting just largely inconclusive local imprints in local observational temperatures during the instrumental period ... ".

MC5 Section 2.2, page 6, line 3-4. 'Since the primary focus... oscillatory behavior associated with internal climate variability…' This may read a bit misleading because the focus of the study is also considering external forcings that influence drought. Perhaps would it be a better argument here that the external forcing signal is disregarded from the Mann et al series by subtracting the 70 yr moving average of the NH mean temperatures?

Thank you for the suggestion – the respective sentence has been replaced with: "To limit the presence of long-term trends in the Mann et al. data, largely reflecting external forcing rather than manifestation of internal climate dynamics, the series has been detrended by subtracting the 70-year moving average of the northern hemisphere mean temperature, also provided by Mann et al. (2009); ... "

MC6 Section 2.2, page 6, line 3-4. 'Since the primary focus... oscillatory behavior associated with internal climate variability…' Line 15-16. 'Again, due to the presence of a strong trend component in the Mann et al series, detrending…. ' Did the authors in this paper do this or was the detrended series obtained from elsewhere? If so, please include a reference.

This is something we did ourselves – the procedure (i.e., a simple subtraction of smoothed northern hemispheric temperature) is described in the fifth and sixth paragraphs of Sect. 2.2, when introducing the series approximating ENSO, AMO and PDO.

MC7 Section 2.2, page 6, line 24-32. 'For the purposes of this study, it was also analyzed in the form of annual NAO index values, extended to the year 2006 by… Jones et al (1997)'
I found the last comment regarding Jones et al (1997) confusing, but maybe it was my misunderstanding. I suggest that the text includes clear statements on the strategy to address drought for different seasons/timescales in coordination/correspondence with those of the predictors used. I see that more clear statements are included in Section 3, page 7, lines ~10. I just suggest making this as clear as possible to the reader.

The comment referring to the Jones et al. (1997) NAO index merely explains that the Luterbacher et al. (2002) NAO reconstruction, available until 2001, was extended by the observational Jones et al. data for the period 2002-2006 (so that full 1501-2006 period could be used for multiple linear regression). As the reviewer states, specification of the (sub)periods used in our analysis is then given in Sect. 3, as a part of the methodology overview.

MC8 Section 4.1, page 8, line 15. '… or by total anthropogenic forcing including the effects of man-made aerosols' Is this really so? Typically the effect of aerosols delays that of GHG because of their relative cooling. Thus a better correspondence between temperatures and

anthropogenic forcing can be achieved when aerosols are considered. Check IPCC 2013 and perhaps rephrase argument.
In any case I understand the trends of drought are quite small and the effect would be difficult to discern between GHG and aerosols, as also the authors have commented in their response.

> Indeed, from a physical point of view, the effects of aerosols are essential (albeit still quite uncertain regarding their magnitude). However, from the perspective of linear regression, the standardized regression coefficients (presented in our analysis) would be almost identical for two versions of a given predictor strongly resembling each other in shape. Specifically, the GHG-only and GHG+aerosols radiative forcing series are very strongly correlated (their Pearson correlation is 0.995 for the annual Meinshausen et al. (2011) data over the 1765-2010 period). Use of a forcing series involving aerosols would therefore produce results very similar to the those presented in our manuscript – this is mentioned in the first paragraph of Sect. 4.1.

MC9 Section 5, page 12, line 31. '… it may be speculated that the responses in the seasonal data are tied to inter-annual…'
Wouldn't this be evident in the crosswavelet analysis?

> Not necessarily, since the links may not pertain to a specific frequency or frequency band, strong enough in both signals to produce a statistically significant response in the cross-wavelet spectrum (a regression mapping may be more sensitive in this regard, as it does not consider individual frequencies separately and does not rely on a specific shape of the wavelet). (To be honest, we did not actually examine the cross-wavelets for season-specific series, partly because of the higher noise levels compared to the annual versions, and partly because of the high amount of possible combinations.)

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

Jiří Mikšovský[1,4], Rudolf Brázdil[2,4], Miroslav Trnka[3,4], Petr Pišoft[1]

[1]Department of Atmospheric Physics, Charles University, Prague, Czech Republic

[2]Institute of Geography, Masaryk University, Brno, Czech Republic

[3]Institute of Agrosystems and Bioclimatology, Mendel University, Brno, Czech Republic

[4]Global Change Research Institute, Czech Academy of Sciences, Brno, Czech Republic

Correspondence to: Jiří Mikšovský (jiri@miksovsky.info; Department of Atmospheric Physics, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, 18000 Prague, Czech Republic)

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 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 (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, especially in summer, while no clear signature of solar activity was found. In addition to identification of the links themselves, their temporal stability and 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). 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).

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 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 Palmer Drought Severity Index – 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 climate forcings and large-scale internal 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 forcings and large-scale climate variability modes in series of drought indices in the Czech Lands during the 1805–2012 period. The authors demonstrated the importance of the North Atlantic Oscillation phase and of the aggregate effect of anthropogenic forcings. Baek et al. (2017) applied correlation analysis to investigate teleconnection patterns between PDSI in multiple regions across the northern hemisphere and activity of several climate variability modes, with noteworthy responses of European droughts indicated especially for NAO, ENSO and PDO. 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). In addition to an analysis of potential drought-relevant links in the climate system, attention is paid to their temporal stability and (mis)match of results based on climate reconstruction data from different sources. Regression and wavelet analysis 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 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 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 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. As a result, a 100-member ensemble of distributions of monthly precipitation totals for each season and year was obtained. These distributions were then applied to calculation of indices for every year in the 1501–1803 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. Note also that despite the profound similarity in temporal variations of individual drought indices, manifesting in their strong mutual correlation (Pearson correlation coefficient *r* = 0.93 for the annual values of SPI-SPEI, *r* = 0.83 for SPI-PDSI, *r* = 0.88 for SPEI-PDSI over the 1501-2006 period), each of them emphasizes different aspects of meteorological droughts, be they simple precipitation sums captured by SPI, evapotranspiration variations considered by SPEI, or longer-term soil moisture status embodied by PDSI. Hereinafter, results for multiple indices are therefore presented and discussed, with regard to their common features as well as mutual contrasts.

2.2 Explanatory variables

Due to the multitude of climate-defining ~~factors~~influences 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 (external forcings) and 3 (internal climate variability modes), supplemented by wavelet spectra for the signals with notable oscillatory components in Fig. ~~6~~7.

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. 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 GHG concentrations are accessible to relatively accurate reconstruction using ice cores, their combined radiative forcing was considered as a potential formal descriptor of the long-term trends in the drought series studied 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 obtained from the online database of the Institute for Atmospheric and Climate Science, ETH Zurich~~.~~, and approximate formulas provided in IPCC (2001, Table 6.2).

While variations in solar activity typically leave no ~~clear~~or just weak imprint ~~on the climatic conditions of the~~in lower ~~troposphere~~tropospheric observational time series 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 (TSI) by Lean et al. (2018) was used as the primary descriptor of solar activity. With data available 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 the 1610–2006 period.

Unlike variations in solar activity or concentrations of 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~~Fischer et al., 2007), but exhibiting just largely inconclusive ~~local~~ imprints in local observational temperatures 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~~To limit the ~~primary focus~~presence of ~~this study centers upon oscillatory behavior associated with~~long-term trends in the Mann et al. data, largely reflecting external forcing rather than manifestation of internal climate ~~variability~~dynamics, 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. 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. ~~6c~~7c, 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~~especially 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, 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 Mann et al. series, 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~~2005) 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 detrimental, given their higher degrees of freedom and higher sensitivity to 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 series were analyzed in the annual time step, either as values constituting mean for the entire year, or as values pertaining to a single season of each year in the usual climatological sense: 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. 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 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. 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 – 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 Regression-estimated drought responses

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 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 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 1501–1850 era (Fig. 4b), in which the GHG signal is mostly featureless. This pattern also appears for individual seasons, with the GHG–temperature link at its relative strongest during SON (Fig. 5). The formal association of 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 very strong correlation between the respective time series, ~~very~~quite similar results would have been obtained if the GHG forcing series was replaced with a predictor representing just CO_2-related effects, or by total anthropogenic forcing including the effects of man-made aerosols.

There is a lack of significant imprint from solar activity in our target series when Lean (2018) solar irradiance data are used for the 1501–2006 period (Fig. 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. While a negative response borderline significant ~~response~~at the 95% level 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).~~6e. A statistically significant solar-related signal was also absent in all individual seasons except for SON (Fig. ~~5).~~5), and non-significance of the imprint of solar activity was indicated when the Coddington et al. (2016) total solar irradiance series was used as a proxy for solar activity in the 1610–2006 period (Fig. 6d). Overall, our results do not seem to support existence of a robust solar-induced component in the time series analyzed.

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 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, ~~especially~~strongest during summer, when a response borderline ~~statistically~~ significant ~~response~~ at the 95% level 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 when the ENSO reconstruction by Li et al. (2011) was used, even though there was a slight tendency towards higher temperature during positive ENSO phase (Fig. 4). This tendency was even stronger (and borderline statistically significant at the 95% level) for the Mann et al. (2009) ENSO data (Fig. ~~S1i~~6i), regardless of the markedly different temporal variability 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 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 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~~6f), with the statistical significance of the link lower than for the Mann et al. data. The existence of a robust connection is therefore uncertain, especially considering previously reported low AMO influence during the instrumental period (Brázdil et al., 2015b; Mikšovský et al., 2016b). There is a 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 significant in the earlier part of the series (1501–1850), especially for PDSI. 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~~6g) or Shen et al. (2006 – Fig. ~~S1h~~6h), 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 at the 95% level 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 just marginally similar for the Ortega et al. (2015) data, ~~although~~ only statistically significant for temperature, and with no response in case of precipitation (Fig. ~~S1k~~6k). 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~~6j); 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 Shared periodicities between drought indices and explanatory factors

Although Brázdil et al. (2015a) demonstrated well-pronounced inter-annual and inter-decadal variations in the Czech MAM–JJA drought data, these were predominantly irregular. As follows from Figs. 1 and ~~6~~7, 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 or the approximately 70-year periodicity of the North Atlantic sea-surface temperature, typically ascribed to AMO (note also that although this periodicity is noticeable in the wavelet spectra of both AMO series here, it tests as statistically significant only from the 18th century onwards in the Mann et al. (2009) data – Fig. ~~6d~~7d). Nonetheless, partial interactions at specific oscillatory periods are a possibility, potentially detectable through cross-wavelet analysis. The respective spectra are visualized in Fig. ~~7~~8 (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~~S1 in the Supplement.

While an approximately 11-year oscillation is one of the defining features of total solar irradiance series (Fig. ~~6b~~7b), 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~~8a). 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~~8b) and PDO (Fig. ~~7c~~8c). These are 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 oscillations is, however, stable throughout the entire period analyzed; 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 be found in the cross-wavelet spectra involving drought indices. However, when the reconstruction by Gray et al. (2004) was used as source for the AMO variability, only 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~~S1a). Similar behavior was also detected for the PDO reconstruction by Shen et al. (2006; Fig. ~~S2c~~S1c), while no significant periodicity match was found for the PDO data by MacDonald and Case (2005; Fig. ~~S2b~~S1b).

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~~8d). 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 (Fig. ~~S2d~~S1d).

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~~8e). 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~~S1e). 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).

5 Discussion

Brázdil et al. (2015a) analyzed imprints of climate forcings in series of six 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 NAO phase and of the aggregate effect of anthropogenic forcing, driven particularly by increasing 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 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 GHGs post 1850 is ~~clearly~~ correlated with the increased probability of temperature-associated 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 consistent significant links suggests that the impacts of solar variations on the drought regime are negligible in central Europe, 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 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 DJF, and only when Li et al. (2011) data were used as the predictor. 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 at the 95% level 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 than 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, most prominent in summer. Our results conform well to the findings by ~~Fisher~~Fischer 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 analysis by Gao and Gao (2017), who 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 MAM and JJA hydroclimate over Europe and the Mediterranean during the last millennium by Rao et al. (2017) indicated wet conditions 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., 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 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~~).~~; Baek et al., 2017). 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 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. 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~~S2b), 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~~6b). On the other hand, AMO alone produces no significant links to drought indices (Fig. ~~S1b~~6b). To investigate this behavior further, the AMO/PDO pair was replaced with their mean value and their difference (note that this setup formally corresponds to the outcomes of unrotated principal component analysis applied to a bi-variate system consisting of the AMO and PDO index series, with the mean value responsible for 88% of total variance of the AMO/PDO pair and the difference responsible for the remaining 12%). Quite surprisingly, a more significant connection to the series of Czech drought indices was indicated for the AMO-PDO difference (all responses statistically significant at the 99% level) rather than their common value (Fig. S1c6c). This suggests that the contrast between the temperature anomalies in the northern Atlantic and northern Pacific, in addition to their individual variability, may be potentially influential in the context of the 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. S1f6f). 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. S3cS2c).

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 in absolute value over their respective overlap periods. (r = -0.17 being the correlation between the Mann et al. and MacDonald and Case data). Clear differences between the reconstructions are also apparent in the cross-wavelet spectra (Fig. S3cS2c). 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 suitablecan be deemed of particular interest for future analyses concerned with central European climate. Even so, it should be emphasized that different reconstructions emphasize different aspects of the climate subsystem in question and our results should not be considered a proof of inherent superiority of any of them.

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. 7e8e), 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. S89, 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 temperature-related results obtained with the Luterbacher et al. (2002) data were ~~also largely~~partly confirmed by the Ortega et al. (2015) reconstruction for the 1501-~~2006~~1969 period, although statistical significance of the ~~links to Czech drought indices~~link was generally lower (Fig. ~~S1k~~6k); 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 some of the cases presented above: it is about 0.06 for SPI or precipitation at annual resolution in the 1501–2006 period (Fig. 4a). A slightly higher value (R^2 = 0.11) was achieved for the temperature-sensitive SPEI, and even higher (R^2 = 0.28) for temperature 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~~S4 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 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~~S3), 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.

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~~S5); 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~~S6). 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~~6a). 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 was employed to study the stability of the NAO-related links, such an approach is problematic for the factors dominated by variations at long periods (such as AMO). In this regard, cross-wavelet transform provided some extra insight; it appears that while periodic oscillations do not dominate Czech drought indices, some specific time-scales are involved in the interactions between our target and explanatory variables. 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 understand these links and their implications, a transition to more complex regression methods 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 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) GHGs concentration (and corresponding radiative forcing) matches the long-term trend component in the central European temperature quite well. This warming is then also reflected in a drying tendency in the temperature-sensitive drought indices ~~quite well~~ (SPEI and PDSI~~, in addition to temperature itself).~~), although not always in a statistically significant manner. 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 pre-instrumental and 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 consistent 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, AMO and (especially) PDO appear to be tied to decadal and multi-decadal components in (at least some) drought indices. Even more curiously, ~~a ~~more significant drought ~~component appears~~components appear to be ~~tied~~linked to the difference between AMO and PDO phases rather than to their common ~~component~~value. Further validation will be, however, needed to verify whether this behavior is a manifestation of actual physical ~~links, as~~relationships, especially considering that it only appears for some of the AMO/PDO reconstructions in our analysis.

(iv) NAO was reaffirmed as a powerful driver of drought variability in this analysis. For the primary NAO reconstruction in ~~the~~our 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 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 documentary- and proxy-based data.

Acknowledgements

This study was supported by the Czech Science Foundation through grant reference 17-10026S. The *biwavelet* package by T. C. Gouhier and A. Grinsted was used to calculate and visualize the wavelet and cross-wavelet spectra in the R language environment. Tony Long (Svinošice) is acknowledged for English style correction.

References

Anet, J. G., Muthers, S., Rozanov, E. V., Raible, C., Stenke, A., Shapiro, A. I., Brönnimann, S., Arfeuille, F. X., Brugnara, Y., Beer, J., Steinhilber, F., Schmutz, W., and Peter, T.: Impact of solar versus volcanic activity variations on tropospheric temperatures and precipitation during the Dalton Minimum, Clim. Past, 10, 921–938, doi: 10.5194/cp-10-921-2014, 2014.

Baek, S. H., Smerdon, J. E., Coats, S., Williams, A. P., Cook, B. I., Cook, E. R., and Seager, R.: Precipitation, Temperature, and Teleconnection Signals across the Combined North American, Monsoon Asia, and Old World Drought Atlases, J. Clim., 30, 7141-7155, doi: 10.1175/JCLI-D-16-0766.1, 2017.

Benestad, R. E.: Solar Activity and Earth's Climate, Springer and Praxis Publishing, Berlin, Chichester, 287 pp., 2003.

Bice, D., Montanari, A., Vučetić, V., and Vučetić, M.: The influence of regional and global climatic oscillation on Croatian climate, Int. J. Climatol., 32, 1537–1557, doi: 10.1002/joc.2372, 2012.

Brands, S.: Which ENSO teleconnections are robust to internal atmospheric variability?, Geophys. Res. Lett., 44, 1483–1493, doi: 10.1002/2016GL071529, 2017.

Brázdil, R., Dobrovolný, P., Luterbacher, J., Moberg, A., Pfister, C., Wheeler, D., and Zorita, E.: European climate of the past 500 years: new challenges for historical climatology, Clim. Change, 101, 7–40, doi: 10.1007/s10584-009-9783-z, 2010.

Brázdil, R., Dobrovolný, P., Trnka, M., Büntgen, U., Řezníčková, L., Kotyza, O., Valášek, H., and Štěpánek, P.: Documentary and instrumental-based drought indices for the Czech Lands back to AD 1501, Clim. Res., 70, 103–117, doi: 10.3354/cr01380, 2016a.

Brázdil, R., Dobrovolný, P., Trnka, M., Kotyza, O., Řezníčková, L., Valášek, H., Zahradníček, P., and Štěpánek, P.: Droughts in the Czech Lands, 1090–2012 AD, Clim. Past, 9, 1985–2002, doi: 10.5194/cp-9-1985-2013, 2013.

Brázdil, R., Pfister, C., Wanner, H., von Storch, H., and Luterbacher, J.: Historical climatology in Europe – the state of the art, Clim. Change, 70, 363–430, doi: 10.1007/s10584-005-5924-1, 2005.

Brázdil, R., Raška, P., Trnka, M., Zahradníček, P., Valášek, H., Dobrovolný, P., Řezníčková, L., Treml, P., Stachoň, Z.: The Central European drought of 1947: causes and consequences, with particular reference to the Czech Lands. Climate Research, 70, 161–178, doi: 10.3354/cr01387, 2016b.

Brázdil, R., Řezníčková, L., Valášek, H., Dolák, L., and Kotyza, O.: Climatic effects and impacts of the 1815 eruption of Mount Tambora in the Czech Lands, Clim. Past, 12, 1361–1374, doi: 10.5194/cp-12-1361-2016, 2016c.

Brázdil, R., Řezníčková, L., Valášek, H., Dolák, L., and Kotyza, O.: Climatic and other responses to the Lakagígar 1783 and Tambora 1815 volcanic eruptions in the Czech Lands, Geografie, 122, 147–168, 2017.

Brázdil, R., Trnka, M., Dobrovolný, P., Chromá, K., Hlavinka, P., and Žalud, Z.: Variability of droughts in the Czech Republic, 1881–2006, Theor. Appl. Climatol., 97, 297–315, doi: 10.1007/s00704-008-0065-x, 2009.

Brázdil, R., Trnka, M., Mikšovský, J., Řezníčková, L., and Dobrovolný, P.: Spring-summer droughts in the Czech Land in 1805–2012 and their forcings, Int. J. Climatol., 35, 1405–1421, doi: 10.1002/joc.4065, 2015a.

Brázdil, R., Trnka, M., Řezníčková, L., Balek, J., Bartošová, L., Bičík, I., Cudlín, P., Čermák, P., Dobrovolný, P., Dubrovský, M., Farda, A., Hanel, M., Hladík, J., Hlavinka, P., Janský, B., Ježík, P., Klem, K., Kocum, J., Kolář, T., Kotyza, O., Krkoška Lorencová, E., Macků, J., Mikšovský, J., Možný, M., Muzikář, R., Novotný, I., Pártl, A., Pařil, P., Pokorný, R., Rybníček, M., Semerádová, D., Soukalová, E., Stachoň, Z., Štěpánek, P., Štych, P., Treml, P., Urban, O., Vačkář, D., Valášek, H., Vizina, A., Vlnas, R., Vopravil, J., Zahradníček, P., and Žalud, Z.: Sucho v českých zemích: Minulost, současnost, budoucnost (Drought in the Czech Lands: Past, Present, and Future). Centrum výzkumu globální změny AV ČR, v.v.i., Brno, 2015b.

Briffa, K. R., van der Schrier, G., and Jones, P. D.: Wet and dry summers in Europe since 1750: evidence of increasing drought, Int. J. Climatol., 29, 1894–1905, doi: 10.1002/joc.1836, 2009.

Brönnimann, S.: Climatic Changes Since 1700, Springer, Cham, Heidelberg, New York, Dordrecht, London, 360 pp., 2015.

Büntgen, U., Brázdil, R., Dobrovolný, P., Trnka, M., and Kyncl, T.: Five centuries of Southern Moravian drought variations revealed from living and historic tree rings, Theor. Appl. Climatol., 105, 167–180, doi: 10.1007/s00704-010-0381-9, 2011a.

Büntgen, U., Brázdil, R., Frank, D., and Esper, J.: Three centuries of Slovakian drought dynamics, Clim. Dyn., 35, 315–329, doi: 10.1007/s00382-009-0563-2, 2010a.

Büntgen, U., Brázdil, R., Heussner, K.-U., Hofmann, J., Kontic, R., Kyncl, T., Pfister, C., Chromá, K., and Tegel, W.: Combined dendro-documentary evidence of Central European hydroclimatic springtime extremes over the last millennium, Quat. Sci. Rev., 30, 3947–3959, doi: 10.1016/j.quascirev.2011.10.010, 2011b.

Büntgen, U., Trnka, M., Krusic, P. J., Kyncl, T., Kyncl, J., Luterbacher, J., Zorita, E., Ljungqvist, F. C., Auer, I., Konter, O., Schneider, L., Tegel, W., Štěpánek, P., Brönnimann, S., Hellmann, L., Nievergelt, D., and Esper, J.: Tree-ring amplification of the early nineteenth-century summer cooling in central Europe, J. Clim., 28, 5272–5288, doi: 10.1175/JCLI-D-14-00673.1, 2015.

Büntgen, U., Trouet, V., Frank, D., Leuschner, H. H., Friedrichs, D., Luterbacher, J., and Esper, J.: Tree-ring indicators of German summer drought over the last millennium, Quat. Sci. Rev., 29, 1005–1016, doi: 10.1016/j.quascirev.2010.01.003, 2010b.

Canty, T., Mascioli, N. R., Smarte, M. D., and Salawitch, R. J.: An empirical model of global climate – Part 1: A critical evaluation of volcanic cooling, Atmos. Chem. Phys., 13, 3997–4031, doi: 10.5194/acp-13-3997-2013, 2013.

Coddington, O., Lean, J., Pilewskie, P., Snow, M., and Lindholm, D.: A solar irradiance climate data record, Bull. Am. Met. Soc., 97, 1265–1282, doi: 10.1175/BAMS-D-14-00265.1, 2016.

Cook, E. R., Seager, R., Kushnir, Y., Briffa, U., Büntgen, D., Frank, P., Krusic, J., Tegel, W., Van der Schrier, G., Andreu-Hayles, L., Baillie, M., Baittinger, C., Billamboz, A., Bleicher, N., Bonde, N., Brown, D., Carrer, M., Cooper, R., Čufar, K., Dittmar, C., Esper, J., Griggs, C., Gunnarson, B., Günther, B., Gutierrez, E., Helama, S., Herzig, F., Heussner, K.-U., Hofman, J., Janda, P., Kontic, R., Köse, N., Kyncl, T., Kristof, H., Levanič, T., Linderholm, H., Manning, S., Melvin, T. M., Neuwirth, B., Nicolussi, K., Siem, A., Svarva, H., Svoboda, M., Thun, T., Touchan, R., Trotsiuk, V., Trouet, V., Wazny, T., Wilson, R., and Zang, C.: Old World megadroughts and pluvials during the Common Era, Science Advances, 1, e1500561, doi: 10.1126/sciadv.1500561, 2015.

Crowley, T. J. and Unterman, M. B.: Technical details concerning development of a 1200 yr proxy index for global volcanism, Earth Syst. Sci. Data, 5, 187–197, doi: 10.5194/essd-5-187-2013, 2013.

Dai, A.: Characteristics and trends in various forms of the Palmer Drought Severity Index (PDSI) during 1900–2008, J. Geophys. Res., 116, D12115, doi: 10.1029/2010JD015541, 2011.

Diodato, N. and Bellocchi, G.: Historical perspective of drought response in central-southern Italy, Clim. Res., 49, 189–200, doi: 10.3354/cr01020, 2011.

Dobrovolný, P., Brázdil, R., Trnka, M., Kotyza, O., and Valášek, H.: Precipitation reconstruction for the Czech Lands, AD 1501–2010, Int. J. Climatol., 35, 1–14, doi: 10.1002/joc.3957, 2015.

Dobrovolný, P., Moberg, A., Brázdil, R., Pfister, C., Glaser, R., Wilson, R., van Engelen, A., Limanówka, D., Kiss, A., Halíčková, M., Macková, J., Riemann, D., Luterbacher, J., and Böhm, R.: Monthly and seasonal temperature reconstructions for Central Europe derived from documentary evidence and instrumental records since AD 1500, Clim. Change, 101, 69–107, doi: 10.1007/s10584-009-9724-x, 2010.

Domínguez-Castro, F., Ribera, P., García-Herrera, R., Vaquero, J. M., Barriendos, M., and Moreno, J. M.: Assessing extreme droughts in Spain during 1750–1850 from rogation ceremonies, Clim. Past, 8, 705–722, doi: 10.5194/cp-8-705-2012, 2012.

Domínguez-Castro, F., Santisteban, J. I., Barriendos, M., and Mediavilla, R.: Reconstruction of drought episodes for central Spain from rogation ceremonies recorded at the Toledo Cathedral from 1506 to 1900: A methodological approach, Glob. Plan. Change, 63, 230–242, doi: 10.1016/j.gloplacha2008.06.002, 2008.

Dubrovský, M., Svoboda, M. D., Trnka, M., Hayes, M. J., Wilhite, D. A., Žalud, Z., and Hlavinka, P.: Application of relative drought indices in assessing climate-change impacts on drought conditions in Czechia, Theor. Appl. Climatol., 96, 155–171, doi: 10.1007/s00704-008-0020-x, 2009.

Enfield, D. B., Mestas-Nuñez, A. M., and Trimble, P. J.: The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S., Geophys. Res. Lett., 28, 2077–2080, doi: 10.1029/2000GL012745, 2001.

~~Fisher~~Fischer, E. M., Luterbacher, J., Zorita, E., Tett, S. F. B., Casty, C., and Wanner, H.: European climate response to tropical volcanic eruptions over the last half millennium, Geoph. Res. Lett., 34, L05707, doi:10.1029/2006GL027992, 2007.

Gao, Y. and Gao, C.: European hydroclimate response to volcanic eruptions over the past nine centuries, Int. J. Climatol., 37, 4145–4157, doi: 10.1002/joc.5054, 2017.

Gray, L. J., Beer, J., Geller, M., Haigh, J. D., Lockwood, M., Matthes, K., Cubasch, U., Fleitmann, D., Harrison, G., Hood, L., Luterbacher, J., Meehl, G. A., Shindell, D., van Geel, B., and White, W.: Solar influences on climate, Rev. Geoph., 48, RG4001, doi: 10.1029/2009RG000282, 2010.

Gray, S. T., Graumlich L. J., Betancourt J. L., and Pederson G. T.: A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D., Geophys. Res. Lett., 31, L12205, doi:10.1029/2004GL019932, 2004.

Gudmundsson, L. and Seneviratne, S. I.: Anthropogenic climate change affects meteorological drought risk in Europe, Environ. Res. Lett., 11, 044005, doi: 10.1088/1748-9326/11/4/044005, 2016.

Haslinger, K. and Blöschl, G.: Space-time patterns of meteorological drought events in the European Greater Alpine Region over the past 210 year, Water Resour. Res., 53, 9807–9823, doi: 10.1002/2017WR020797, 2017.

Heim, R. R.: Drought indices. A review, In: Wilhite, D. A., ed.: Drought: A Global Assessment. Hazards Disaster Series, Vol. I. Routledge, New York, 159–167, 2000.

IPCC, 2001: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A. (eds.): Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2001.

Jones, P. D., Jonsson, T., and Wheeler, D.: Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland, Int. J. Climatol., 17, 1433–1450, doi:10.1002/(sici)1097-0088(19971115)17:13<1433::aid-joc203>3.0.co;2-p, 1997.

Lean J. L.: Estimating Solar Irradiance Since 850 CE, Earth Space Sci., 5, 133–149, doi: 10.1002/2017EA000357, 2018.

Li, J., Xie, S., Cook, E., Huang, G., D'Arrigo, R., Liu, F., Ma, J., and Zheng, X.: Interdecadal modulation of El Niño amplitude during the past millennium, Nat. Clim. Change, 1, 114–118, doi: 10.1038/nclimate1086, 2011.

Liu, Y., San Liang, X., and Weisberg, R. H.: Rectification of the bias in the wavelet power spectrum, J. Atmos. Ocean. Tech., 24, 2093–2102, doi: 10.1175/2007JTECHO511.1, 2007.

Lohmann, G., Rimbu, N., and Dima, M.: Climate signature of solar irradiance variations: analysis of long-term instrumental, historical, and proxy data, Int. J. Climatol., 24, 1045–1056, doi: 10.1002/joc.1054, 2004.

Luterbacher, J., Xoplaki, E., Dietrich, D., Jones, P. D., Davies, T. D., Portis, D., Gonzalez-Rouco, J. F., von Storch, H., Gyalistras, D., Casty, C., and Wanner, H.: Extending North Atlantic Oscillation reconstructions back to 1500, Atmos. Sci. Lett., 2, 114–124, doi:10.1006/asle.2001.0044, 2002.

MacDonald, G. M. and Case R. A.: Variations in the Pacific Decadal Oscillation over the past millennium, Geophys. Res. Lett., 32, L08703, doi:10.1029/2005GL022478, 2005.

Mann, M., Zhang, Z., Rutherford, S., Bradley, R., Hughes, M., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F.: Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly, Science, 326, 1256–1260, 2009.

McCabe, G. J., Palecki, M. A., and Betancourt, J. L.: Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States, Proc. Natl. Acad. Sci. USA, 101, 4236–4141, doi: 10.1073/pnas.0306738101, 2004.

McKee, T. B., Doesken, N. J., and Kleist, J.: The relationship of drought frequency and duration to time steps, In: Preprints, 8th Conference on Applied Climatology, Anaheim, January 17–22, 179–184, 1993.

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J. F., Matsumoto, K., Montzka, S. A., Raper, S. C. B., Riahi, K., Thomson, A., Velders, G. J. M., and van Vuuren, D. P. P.: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300, Clim. Change, 109, 213–241, doi:10.1007/s10584-011-0156-z, 2011.

Mikšovský, J., Brázdil, R., Štěpánek, P., Zahradníček, P., and Pišoft, P.: Long-term variability of temperature and precipitation in the Czech Lands: an attribution analysis, Clim. Change, 125, 253–264, doi: 10.1007/s10584-014-1147-7, 2014.

Mikšovský, J., Holtanová, E., and Pišoft, P.: Imprints of climate forcings in global gridded temperature data. Earth. Syst. Dyn., 7, 231–249, doi: 10.5194/esd-7-231-2016, 2016a.

Mikšovský, J., Trnka M., and Brázdil R.: Manifestations of climatic teleconnections in Czech drought characteristics, In: Vačkář D., Janouš D. (Eds.): Global Change & Ecosystems, Vol 2. Global Change Research Institute, Czech Academy of Sciences, Brno, 15–26, 2016b.

Mohino, E., Janicot, S., and Bader, J.: Sahel rainfall and decadal to multidecadal sea surface temperature variability, Clim. Dyn., 37, 419–440, doi: 10.1007/s00382-010-0867-2, 2011.

Možný, M., Brázdil, R., Dobrovolný, P., Trnka, M., Potopová, V., Hlavinka, P., Bartošová, L., Zahradníček, P., and Žalud, Z.: Drought reconstruction based on grape harvest dates for the Czech Lands, 1499–2012, Clim. Res., 70, 119–132, doi: 10.3354/cr01423, 2016.

Naumann, G., Alfieri, L., Wyser, K., Mentaschi, L., Betts, R. A., Carrao, H., Spinoni, J., Vogt, J., and Feyen, L.: Global changes in drought conditions under different levels of warming, Geophys. Res. Lett., doi: 10.1002/2017GL076521, 2018.

Noone, S., Broderick, C., Duffy, C., Matthews, T., Wilby, R. L., and Murphy, C.: A 250-year drought catalogue for the island of Ireland (1765–2015), Int. J. Climatol., 37, 239–254, doi: 10.1002/joc.4999, 2017.

Oglesby, R., Feng, S., Hu, Q., and Rowe, C.: The role of the Atlantic Multidecadal Oscillation on medieval drought in North America: Synthesizing results from proxy data and climate models, Glob. Plan. Change, 84–85:56–65, doi: 10.1016/j.gloplacha.2011.07.005, 2012.

Ortega, P., Lehner, F., Swingedouw, D., Masson-Delmotte, V., Raible, C. C., Casado, M., and Yiou, P.: A model-tested North Atlantic Oscillation reconstruction for the past millennium, Nature, 523:71–74, doi:10.1038/nature14518, 2015.

PAGES Hydro2k Consortium: Comparing proxy and model estimates of hydroclimate variability and change over the Common Era, Clim. Past, 13, 1851–1900, https://doi.org/10.5194/cp-13-1851-2017, 2017.

Palmer, W. C.: Meteorological Drought, Office of Climatology Research Paper 45, U.S. Weather Bureau, Washington, 58 pp., 1965.

Piervitali, E. and Colacino, M.: Evidence of drought in Western Sicily during the period 1565–1915 from liturgical offices, Clim. Change, 49, 225–238, doi: 10.1023/A:1010746612289, 2001.

Písek, J. and Brázdil, R.: Responses of large volcanic eruptions in the instrumental and documentary climatic data over Central Europe, Int. J. Climatol., 26, 439–459, doi: 10.1002/joc.1249, 2006.

Politis D. N. and White, H.: Automatic block-length selection for the dependent bootstrap, Economet. Rev., 23, 53–70, doi: 10.1081/ETC-120028836, 2004.

Pongrácz, R., Bogardi, I., and Duckstein, L.: Climatic forcing of droughts: a Central European example, Hydrol. Sci. J., 48, 39–50, doi: 10.1623/hysj.48.1.39.43480, 2003.

Rao, M. P., Cook, B. I., Cook, E. R., D'Arrigo, R. D., Krusic, P. J., Anchukaitis, K. J., LeGrande, A. N., Buckley, B. M., Davi, N. K., Leland, C., and Griffin, K. L.: European and Mediterranean hydroclimate responses to tropical volcanic forcing over the last millennium, Geophys. Res. Lett., 44, 5104–5112, doi: 10.1002/2017GL073057, 2017.

Ryne, S. and Forest, K.: Evidence for increasing variable Palmer Drought Severity Index in the United States since 1895, Sci. Tot. Env., 544, 792–796, doi: 10.1016/j.scitotenvv.2015.11.167, 2016.

Schwander, M., Rohrer, M., Brönnimann, S., and Malik, A.: Influence of solar variability on the occurrence of central European weather types from 1763 to 2009, Clim. Past, 13, 1199–2012, doi: 10.5194/cp-13-1199-2017, 2017.

Shen C., Wang W.-C., Gong W., and Hao. Z.: A Pacific Decadal Oscillation record since 1470 AD reconstructed from proxy data of summer rainfall over eastern China, Geoph. Res. Lett., 33, L03702, doi: 10.1029/2005GL024804, 2006.

Sjolte, J., Sturm, C., Adolphil, F., Vinther, B. M., Werner, M., Lohmann, G., and Muscheler, R.: Solar and volcanic forcing of North Atlantic climate inferred from a process-based reconstruction, Clim. Past, 14, 1179–1194, doi: 10.5194/cp-14-1179-2018, 2018.

Sousa, P. M., Trigo, R. M., Aizpurua, P., Nieto, R., Gimeno, L., and García-Herrera, R.: Trends and extremes of drought indices throughout the 20th century in the Mediterranean, Nat. Hazards Earth Syst. Sci., 11, 33–51, doi: 10.5194/nhess-11-33-2011, 2011.

Spinoni, J., Naumann, G., Carrao, H., Barbosa, P., and Vogt, J.: World drought frequency, duration, and severity for 1951–2010. Int. J. Climatol., 34, 2792–2804, doi: 10.1002/joc.3875, 2014.

Spinoni, J., Naumann, G., Vogt, J., and Barbosa, P.: European drought climatologies and trends based on a multi-indicator approach, Glob. Plan. Change, 127, 50–57, doi: 10.1016/j.gloplacha.2015.01.012, 2015.

Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M. M. B., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M. (eds.): Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 2013.

Sutton, R. T. and Hodson, D. L. R.: Atlantic Ocean Forcing of North American and European Summer Climate, Science, 309: 115-118, doi: 10.1126/science.1112666, 2005.

Todd, B., Macdonald, N., Chiverrell, R. C., Caminade, C., and Hooke, J. M.: Severity, duration and frequency of drought in SE England from 1697 to 2011, Clim. Change, 121, 673–687, doi: 10.1007/s10584-013-0970-6, 2013.

Torrence, C. and Compo G. P.: A practical guide to wavelet analysis, Bull. Am. Met. Soc., 79, 61–78, doi: 10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2, 1998.

Trnka, M., Dubrovský, M., Svoboda, M., Semerádová, D., Hayes, M., Žalud, Z., and Wilhite, D.: Developing a regional drought climatology for the Czech Republic, Int. J. Climatol., 29, 863–883, doi: 10.1002/joc.1745, 2009a.

Trnka, M., Kyselý, J., Možný, M., and Dubrovský, M.: Changes in Central European soil moisture availability and circulation patterns in 1881–2005, Int. J. Climatol., 29, 655–672, doi: 10.1002/joc.1703, 2009b.

Trnka, M., Hayes, M., Jurečka, F., Bartošová, L., Anderson, M., Brázdil, R., Brown, J., Camarero, J. J., Cudlín, P., Dobrovolný, P., Eitzinger, J., Feng, S., Finnessey, T., Gregorič, G., Havlik, P., Hain, C., Holman, I., Johnson, D., Kersebaum, K. C., Ljungqvist, F. C., Luterbacher, J., Micale, F., Hartl-Meier, C., Možný, M., Nejedlik, P., Olesen, J. E., Ruiz-Ramos, M., Rötter, R. P., Senay, G., Vicente Serrano, S. M., Svoboda, M., Susnik, A., Tadesse, T., Vizina, A., Wardlow, B., Žalud, Z., and Büntgen, U.: Prority questions in multidisciplinary drought research, Clim. Res., doi: 10.3354/cr.01509, 2018.

Trouet, V., Esper J., Graham N. E., Baker A., Scourse J. D., and Frank D.: Persistent positive North Atlantic Oscillation mode dominated the Medieval Climate Anomaly, Science, 324, 78–80, doi: 10.1126/science.1166349, 2009.

van der Schrier, G., Barichivich, J., Briffa, K. R., and Jones, P. D.: A scPDSI-based global dataset of dry and wet spells for 1901–2009. J. Geoph. Res., 118, 4025–4048, doi: 10.1002/jgrd.50355, 2013.

van der Schrier, G., Briffa, K. R., Jones, P. D., and Osborn, T. J.: Summer moisture variability across Europe, J. Clim., 19, 2818–2834, doi: 10.1175/JCLI3734.1, 2006.

van der Schrier, G., Efthymiadis, D., Briffa, K. R., and Jones, P. D.: European Alpine moisture variability 1800–2003, Int. J. Climatol., 27, 415–427, doi: 10.1002/joc.1411, 2007.

Veleda, D., Montagne, R., and Araujo, M.: Cross-wavelet bias corrected by normalizing scales, J. Atmos. Ocean Tech., 29, 1401–1408, doi: 10.1175/JTECH-D-11-00140.1, 2012.

Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A multi-scalar drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index – SPEI, J. Climate, 23, 1696–1718, doi: 10.1175/2009JCLI2909.1, 2010.

Vicente-Serrano, S. M., Lopez-Moreno, J. I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J. M., Azorin-Molina, C., Morán-Tejeda, E., Revuelto, J., Trigo, R., Coelho, F., and Espejo, F.: Evidence of increasing drought severity caused by temperature rise in southern Europe, Environ. Res. Lett., 9, 044001, doi: 10.1088/1748-9326/9/4/044001, 2014.

Wells, N., Goddard, S., and Hayes, M.: A self-calibrating Palmer Drought Severity Index, J. Clim., 17, 2335–2351, doi: 10.1175/1520-0442(2004)017<2335:ASPDSI>2.0.CO;2, 2004.

Wilhite, D. A. and Pulwarty, R. S., eds.: Drought and Water Crises. Integrating Science, Management, and Policy. CRC Press, Boca Raton, 541 pp., 2018.

Zahradníček, P., Trnka, M., Brázdil, R., Možný, M., Štěpánek, P., Hlavinka, P., Žalud, Z., Malý, A., Semerádová, D., Dobrovolný, P., Dubrovský, and M., Řezníčková, L.: The extreme drought episode of August 2011–May 2012 in the Czech Republic, Int. J. Climatol., 35, 3335–3352. DOI: 10.1002/joc.4211, 2015.

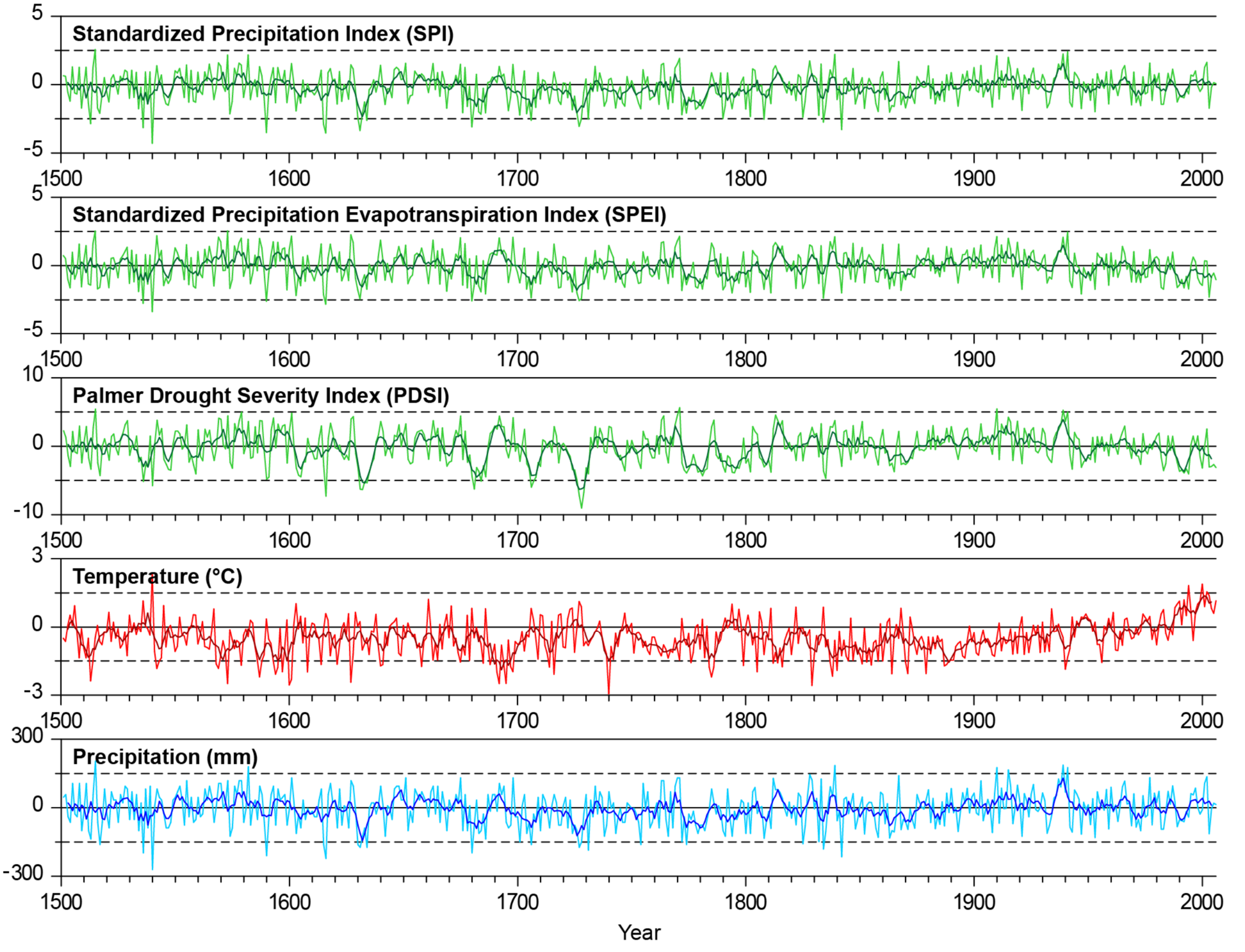


Figure 1. ~~Fluctuations in annual~~Annual series of drought indices, temperature and precipitation anomalies (w.r.t. 1961–1990 reference period) for the Czech Lands in the 1501–2006 period; smoothed by 11-year running means (darker lines).

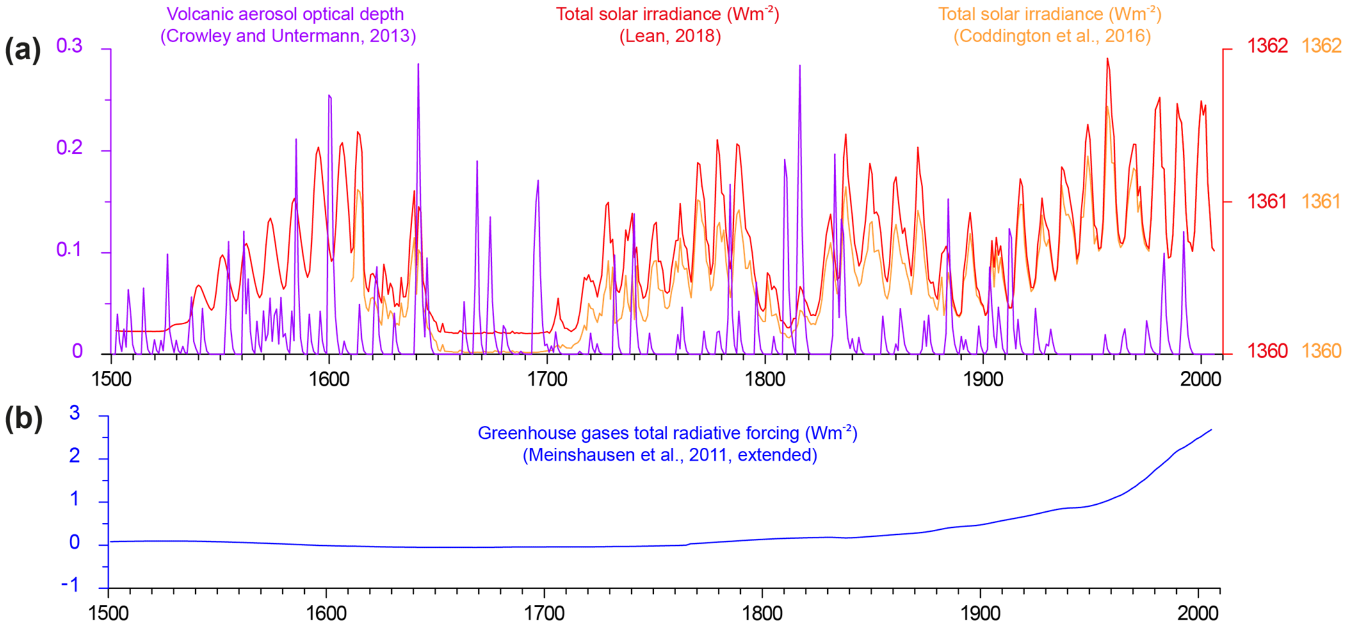


Figure 2. ~~Fluctuations in the annual~~Annual series of external forcing descriptors: (a) volcanic aerosol optical depth and total solar irradiance, (b) greenhouse gases radiative forcing.

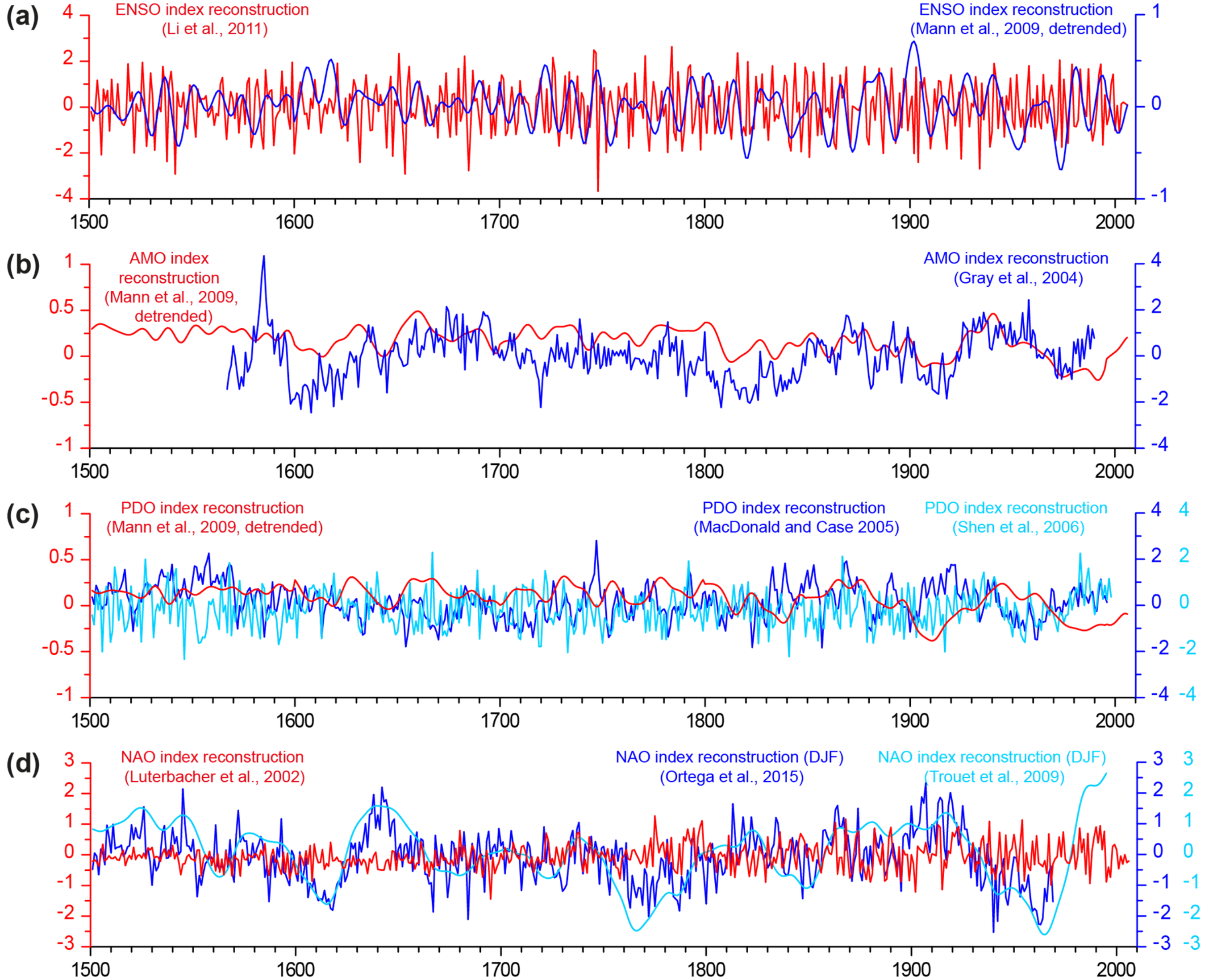


Figure 3. ~~Fluctuations in reconstructed~~Reconstructed annual series of internal climate variability modes: (a) El Niño – Southern Oscillation (ENSO), (b) Atlantic Multidecadal Oscillation (AMO), (c) Pacific Decadal Oscillation (PDO), (d) North Atlantic Oscillation (NAO).

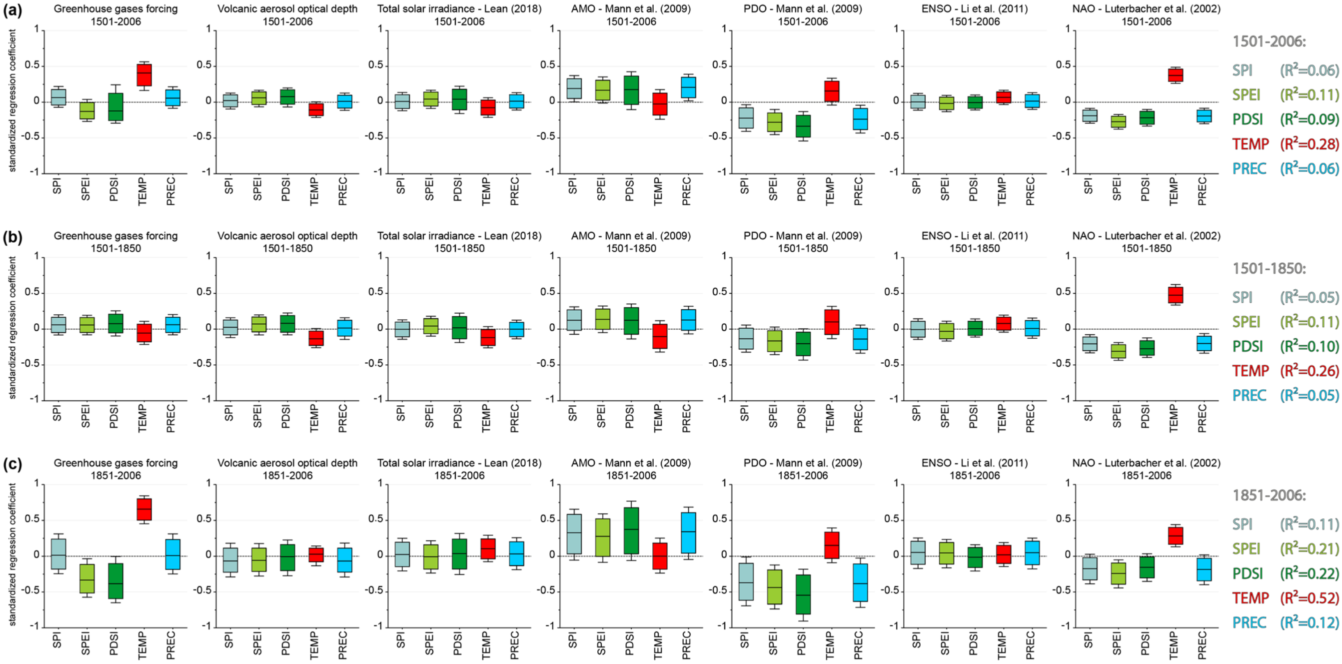


Figure 4. Standardized regression coefficients (central line, with 95% confidence interval shown as the box and 99% confidence interval as the whiskers), obtained by multiple linear regression between the predictands characterizing local Czech climate (drought indices, temperature and precipitation) and a set of explanatory variables representing external forcings and large-scale internal climate variability modes in various periods: (a) 1501–2006, (b) 1501–1850, (c) 1851–2006. R^2: fraction of variance explained by the regression mapping.

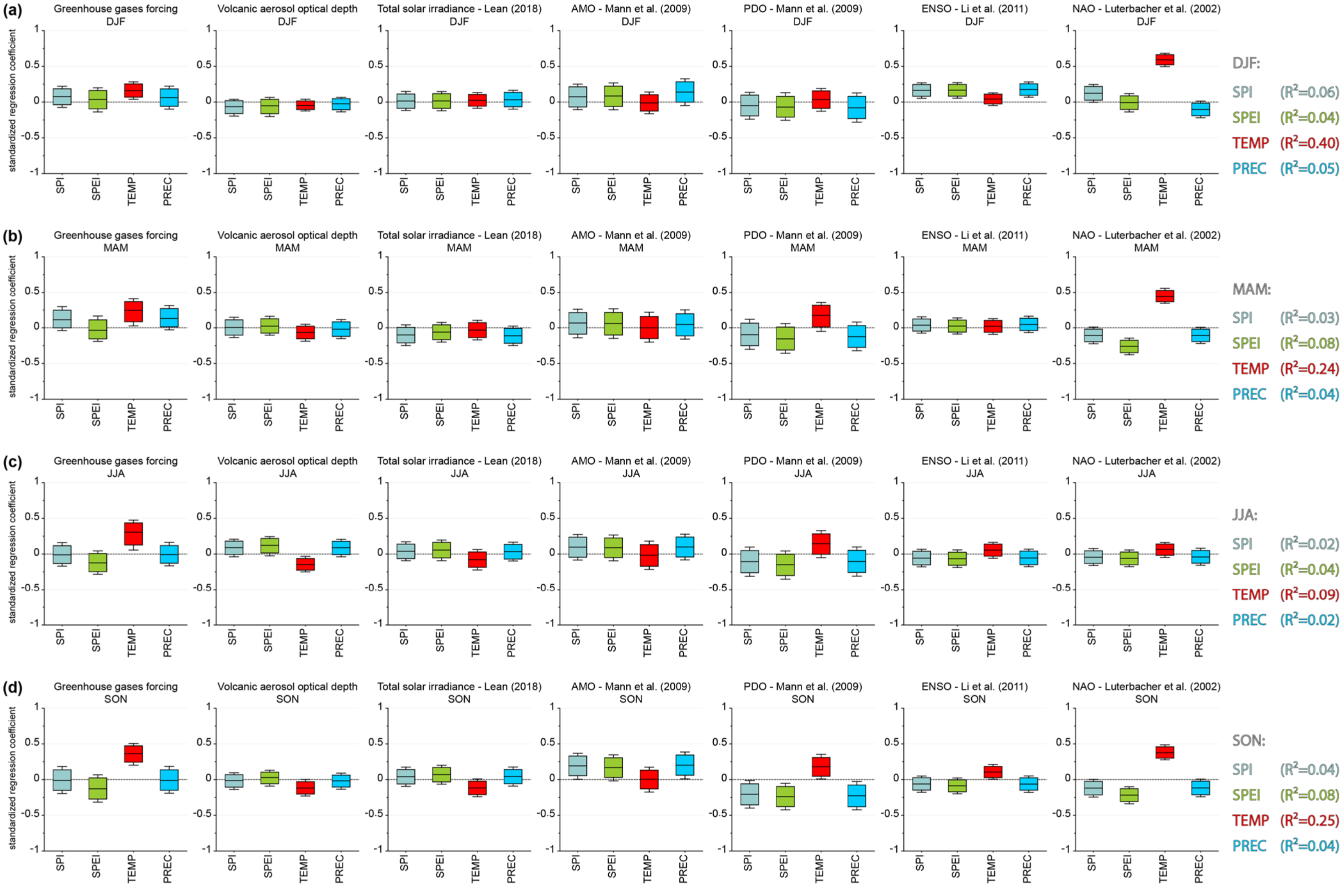
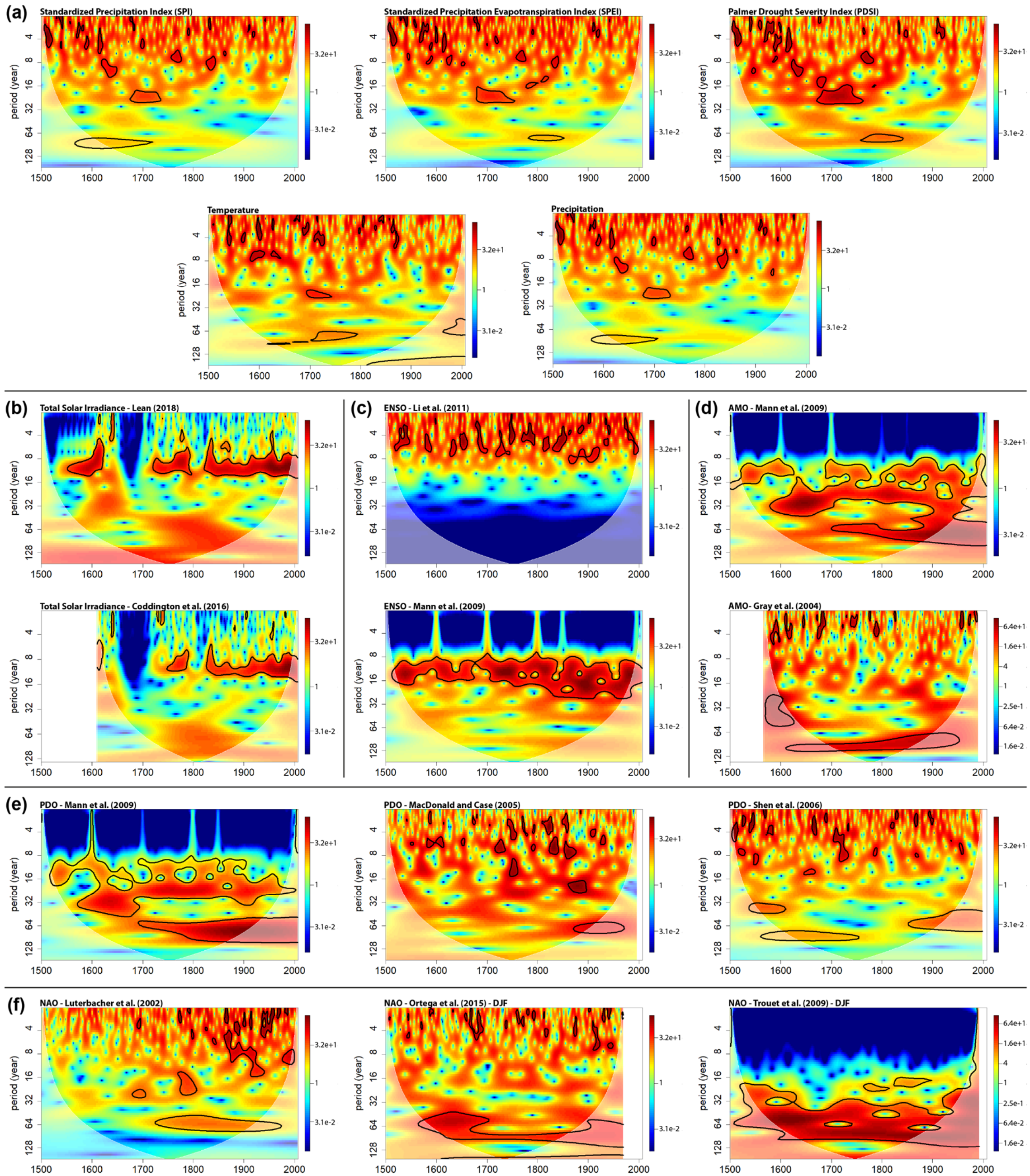


Figure 5. Standardized regression coefficients (central line, with 95% confidence interval shown as the box and 99% confidence interval as the whiskers), obtained by multiple linear regression between the predictands characterizing local Czech climate (drought indices, temperature and precipitation)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


(a)
Standardized Precipitation Index (SPI)
Standardized Precipitation Evapotranspiration Index (SPEI)
Palmer Drought Severity Index (PDSI)
Temperature
Precipitation
(b)
Total Solar Irradiance - Lean (2018)
Total Solar Irradiance - Coddington et al. (2016)
(c)
ENSO - Li et al. (2011)
ENSO - Mann et al. (2009)
(d)
AMO - Mann et al. (2009)
AMO- Gray et al. (2004)
(e)
PDO - Mann et al. (2009)
PDO - MacDonald and Case (2005)
PDO - Shen et al. (2006)
(f)
NAO - Luterbacher et al. (2002)
NAO - Ortega et al. (2015) - DJF
NAO - Trouet et al. (2009) - DJF
period (year)
1500 1600 1700 1800 1900 2000

~~Figure 6.~~

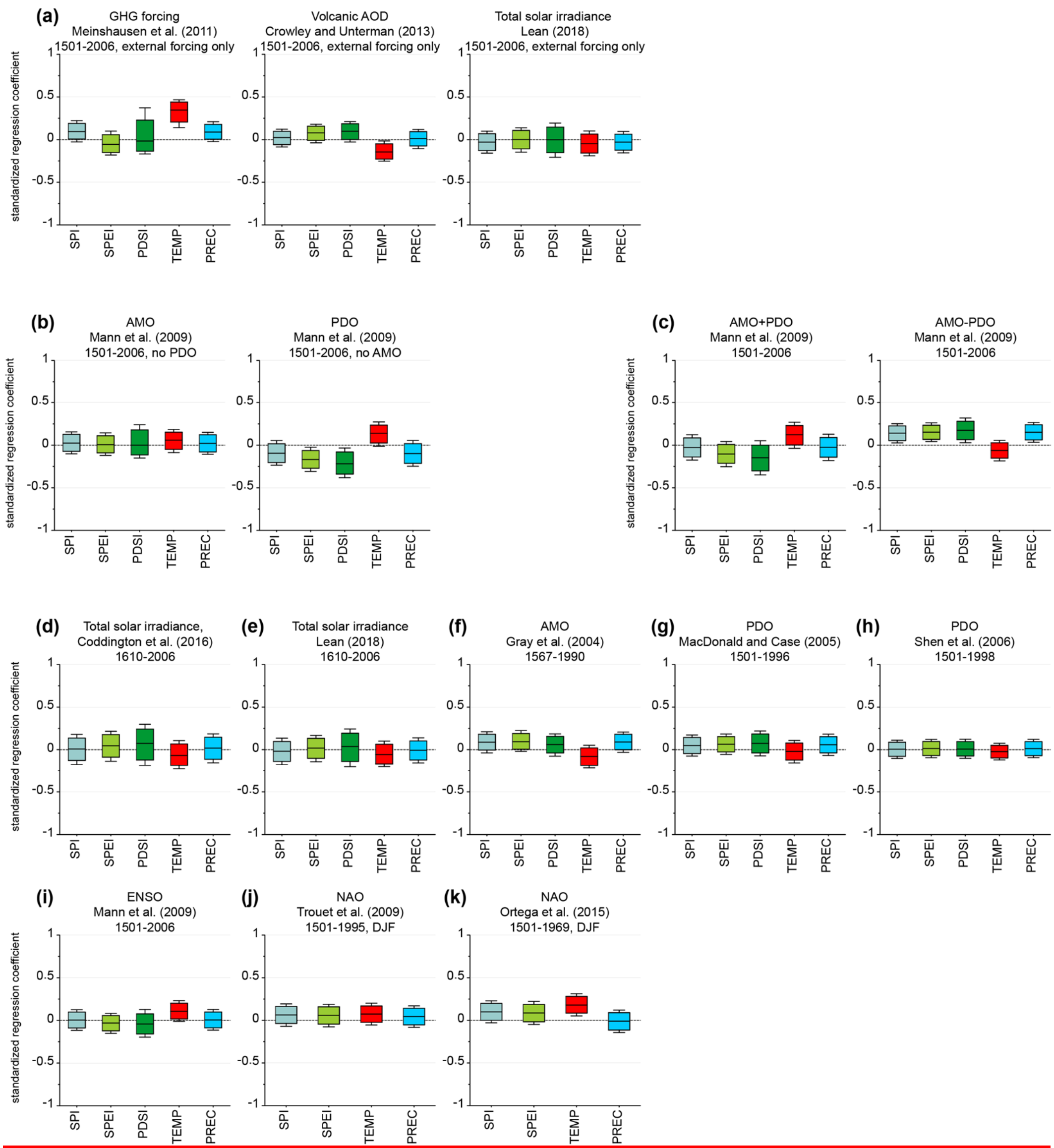


Figure 6. Standardized regression coefficients (central line, with 95% confidence interval shown as the box and 99% confidence interval as the whiskers), obtained by multiple linear regression between the predictands characterizing local Czech climate (drought indices, temperature and precipitation) and (a) a set of explanatory variables representing external forcings only (i.e. a 3-predictor setup involving GHG forcing, volcanic aerosol optical depth and total solar irradiance only), (b) a setup from Fig. 4 with only AMO or only PDO predictor instead of both, (c) a setup from Fig. 4 with AMO and PDO predictors replaced by their mean (AMO + PDO) and difference (AMO –

PDO), (d-k) setups with one of the predictors replaced by its alternative version while keeping the rest same as in Fig. 4 (only coefficients for the modified predictors are shown).

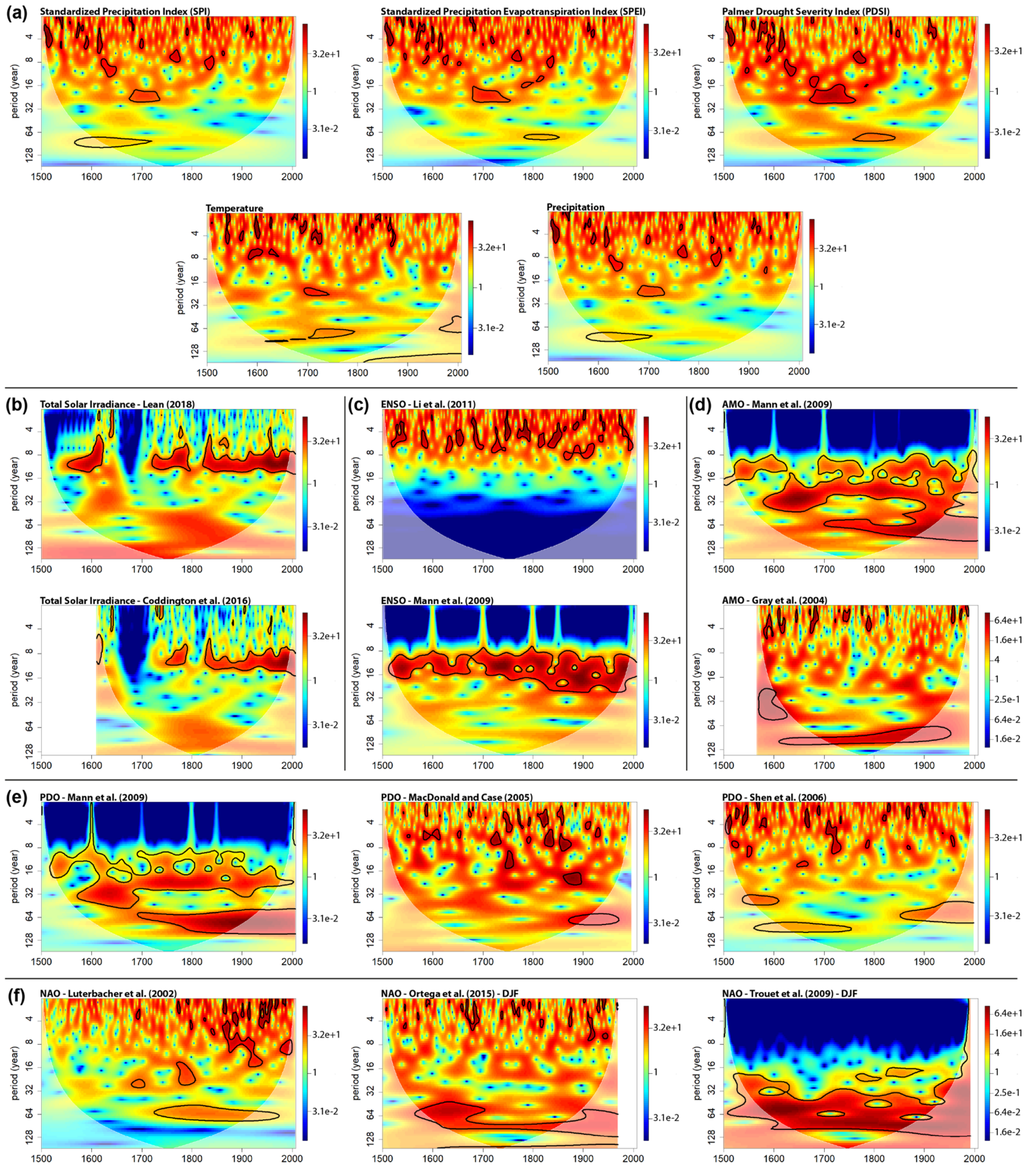
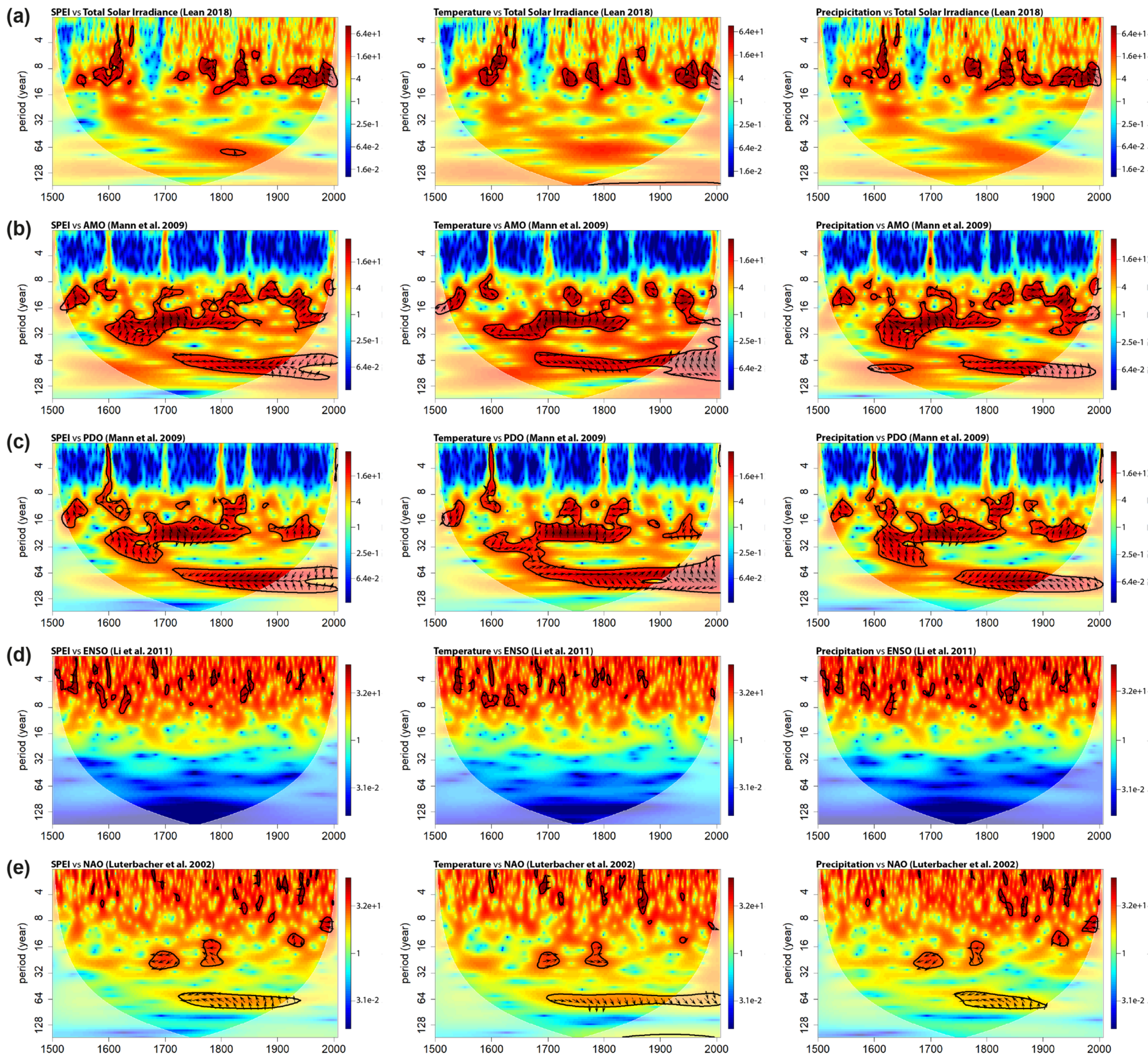


Figure 7. Standardized wavelet power spectra of annual series of (a) Czech drought indices, temperature, precipitation, as well as of individual explanatory variables with prominent oscillatory component: (b) total solar irradiance, (c) ENSO, (d) AMO, (e) PDO, (f) NAO.

Areas enclosed by black line correspond to wavelet coefficients statistically significant at the 95% level, AR(1) process null hypothesis. The lower-contrast areas pertain to the cone of influence, i.e. region with diminished representativeness of the wavelet spectra due to edge effects.


(a)
SPEI vs Total Solar Irradiance (Lean 2018)
Temperature vs Total Solar Irradiance (Lean 2018)
Precipicitation vs Total Solar Irradiance (Lean 2018)
(b)
SPEI vs AMO (Mann et al. 2009)
Temperature vs AMO (Mann et al. 2009)
Precipitation vs AMO (Mann et al. 2009)
(c)
SPEI vs PDO (Mann et al. 2009)
Temperature vs PDO (Mann et al. 2009)
Precipitation vs PDO (Mann et al. 2009)
(d)
SPEI vs ENSO (Li et al. 2011)
Temperature vs ENSO (Li et al. 2011)
Precipitation vs ENSO (Li et al. 2011)
(e)
SPEI vs NAO (Luterbacher et al. 2002)
Temperature vs NAO (Luterbacher et al. 2002)
Precipitation vs NAO (Luterbacher et al. 2002)
period (year)
4 8 16 32 64 128
1500 1600 1700 1800 1900 2000
6.4e+1 1.6e+1 4 1 2.5e-1 6.4e-2 1.6e-2
3.2e+1 1 3.1e-2

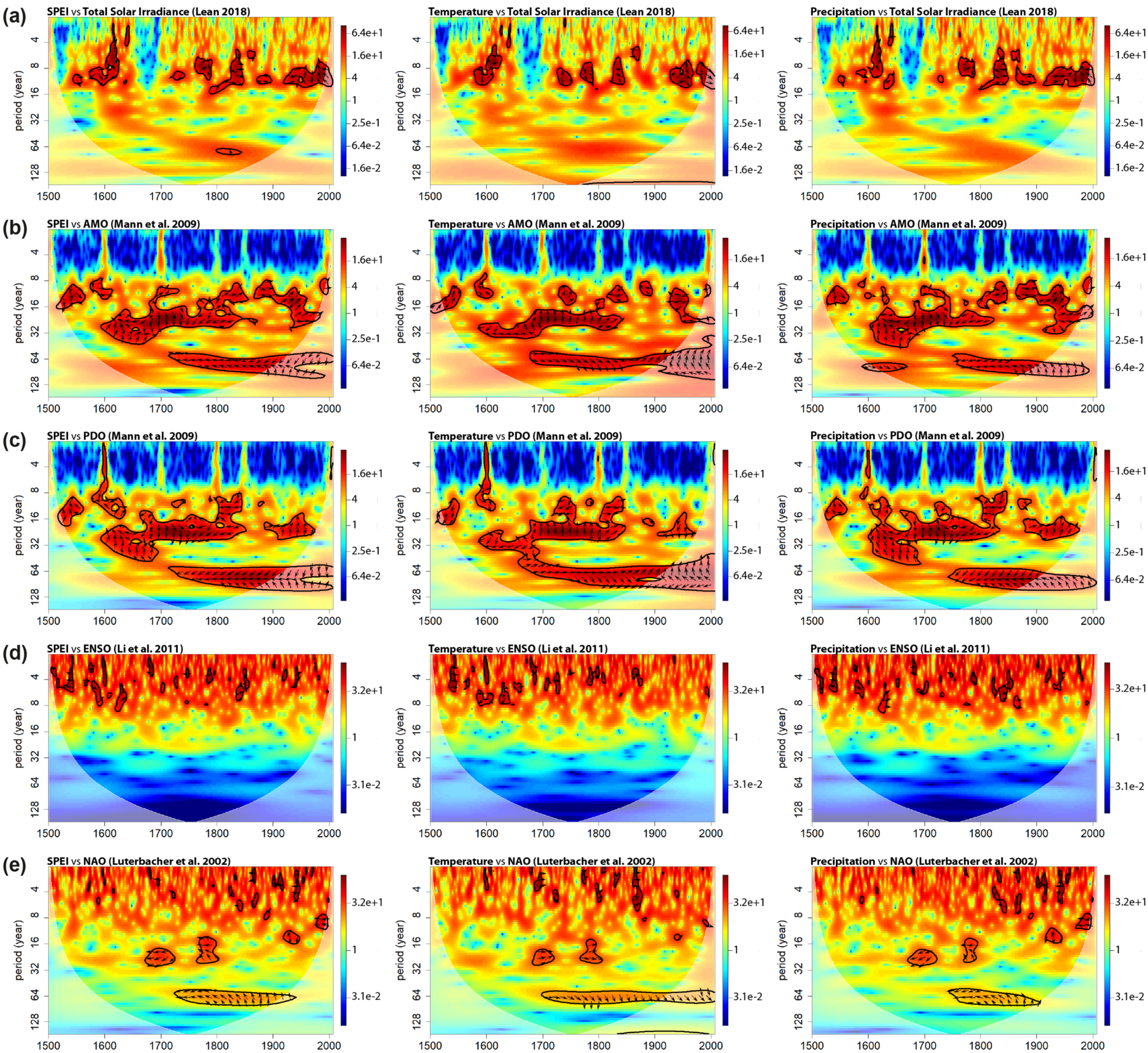


Figure ~~7~~8. Standardized cross-wavelet spectra between series of Czech SPEI, temperature, precipitation and selected explanatory variables with distinct oscillatory component: (a) total solar irradiance, (b) AMO, (c) PDO, (d) ENSO (e) NAO (annual time-step; standardized and bias corrected, as per Veleda et al., 2012). Areas enclosed by black line correspond to cross-wavelet powers statistically significant at the 95% level, 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. The lower-contrast areas pertain to the cone of influence, i.e. region with diminished representativeness of the wavelet spectra due to edge effects.

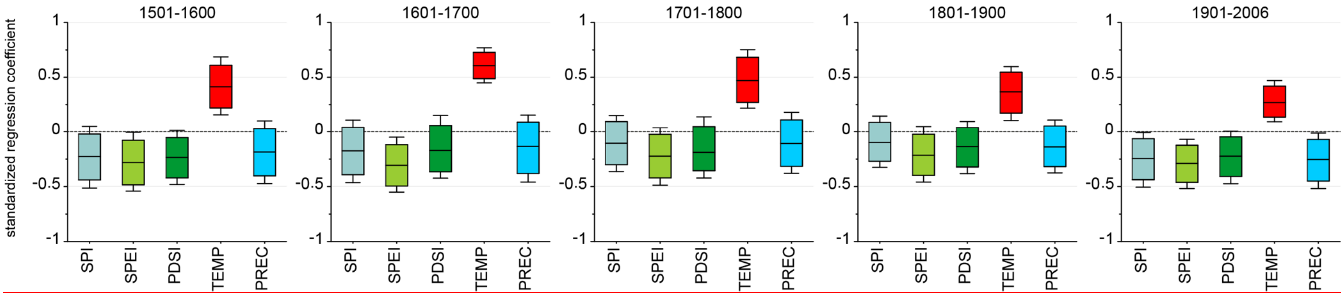


Figure 9. Standardized regression coefficients (central line, with 95% confidence interval shown as the box and 99% confidence interval as the whiskers), obtained for the NAO index (Luterbacher et al., 2002) in five non-overlapping sub-intervals of the 1501-2006 period. Multiple linear regression was employed in a seven-predictor setup identical to the one in Fig. 4 (only coefficients for the NAO index are shown).