Dear editor,

Thank you for your comments, suggestions, and recommendations.

In the following we address each of your major points separately. Your comments are in red font, our replies in normal font.

1. thanks very much for addressing the questions/critics/suggestions of the reviewers. All reviewers mention similar major points with regard to the clarity of the introduction, aim of the study, the presentation of the results, critical aspects related to the choice of instrumental data, reconstruction and models, their interpretation, visualisation of the results as well as the conclusions. Thus, it should be straight forward to revise the manuscript accordingly in agreement with the suggested changes of the authors.

We have rewritten and rearranged the manuscript. We changed the visualisation of results and added additional Figures. We hope this clarifies the presentation and addresses the points made by referees and editor.

2. The authors use SPI as the measure for their analysis. As it is only based on precipitation, I agree that analysis that use temperature do not need to be shown.

a) The revised version thus should include more studies that deal with precipitation and as suggested by the authors in their last section of reviews, incorporate additional precipitation/drought sensitive information.
b) This would mean that the revised version provides a comprehensive analysis of all available precipitation and drought information from parts of the British Isles.

We reduce the discussion of temperature to a minimum, but we would like to point out that the rationale for including temperature was not its influence on the drought index but rather the physical understanding of precipitation anomalies, for instance, whether there is a link to cloudiness variations.

a) The revised version discusses a number of additional studies on precipitation over the South of Great Britain. We use additional data in form of instrumental series, of observational indices, and discuss shortly additional reconstructions. We do not include the analyses of these series in the manuscript, as these are not all in the public domain and we are not willing to compel the original authors to publish their data because of our manuscript.
b) Thus, we are quite comprehensive for the south of Great Britain. We still do not include field reconstructions and we do not include other parts of the British Isles.

3. The (in)consistencies between the various information sources need to be made more clearly as the reviewers suggested.

We hope that the rewriting of the manuscript and the additional discussions clarify what we mean by consistency, what we mean by inconsistency, and which consistencies and inconsistencies we find.

4. It would be important to explain also in more detail why SPI is used and not other drought related measures. SPI is a specific index for meteorological drought with strengths and limitations that need to be discussed (see information for instance in: http://climatedataguide.ucar.edu/climate-data/standardized-precipitation-index-spi
About the choice of an appropriate drought index from a model point of view, the authors might refer to Raible et al. (2017) on "Drought indices revisited-improving and testing of drought indices in a simulation of the last two millennia for Europe", Tellus, 69, 1287492

Introduction, methods section, and discussions now include dedicated paragraphs justifying our choice of the SPI, describing the SPI's shortcomings and advantages, and describing its appropriateness for the region of interest.

5. For instrumental data/reconstruction data the authors might do a detailed screening on the literature for this area and then choose.

We describe now clearly our choice of instrumental data and add these to the initial analyses. We further discuss them.

6. Further, the use of RCM data for comparisons, interpretation, comments that have been risen all reviewers. This point needs to be more clearly addressed, what is the purpose of showing RCM analysis in comparison with instrumental/reconstruction data and how do the analysis go beyond the current state of the art. The authors mention that they will make this point more clear and also move parts in a SOM.

Introduction, methods section, and discussions now include dedicated information and comments on why and how we use the Regional Climate Simulation. The global simulations have been removed from the main manuscript and relocated into a supplementary document.

7. In this context one open issue refers to the suggestion of reviewer 1 to write two different papers rather than implementing everything in one paper, thus removing for instance the model/data comparison and leave it for a new publication. I leave the decision up to the authors, but any decision to include models or exclude them should be clearly explained.

We decide against the option to write two papers on the topic. We regard the comparison of all three sources of information as one of the major points of this manuscript. One point here is that the comparison between reconstructions and observational data is already done in the original publications, although not in terms of SPI. Secondly, as the added value of RCMs is according to your comments still up for discussion, we think including them here may help to show their value. The manuscript as a whole is certainly quite extensive, but we think it forms a unity that would be difficult to split in two parts. We are considering to extend on additional reconstruction data in a complementary manuscript.

8. I agree with Reviewer 1 and 2

a) that have concerns using the tree ring reconstructions, either as they may not reflect precipitation or the season under consideration
b) or that the Trouet et al. jet reconstruction is not an appropriate measure for circulation purposes. With respect to circulation analysis, for the past centuries there are monthly to seasonal large scale SLP and Z500 reconstructions that are based on instrumental pressure and ship log books information. They are more suitable and trustworthy than natural proxy reconstructions and should be used instead.

a) We shortly discuss two isotope based reconstructions.
b) Given the overall length of the manuscript, we decided against including reconstructions of atmospheric dynamics and their comprehensive discussion except for the part where we discuss the literature more extensively.

9. I think it is a valuable comment by reviewer 2 concerning the Rinne et al paper. I am sure that the authors would provide the data for analysis.

We obtained the data and shortly discussed it.

We upload the Supplement now with the manuscript. It will be ultimately deposited at https://osf.io/duyqe/.

Below you may find our final point-by-point reply to the reviews as already posted in the discussion forum on 16 July 2018, a list of relevant changes to the manuscript, and a marked-up version of the manuscript.

Thank you for your helpful comments again.

On behalf of the authors,

Yours sincerely

Oliver Bothe

Clim. Past Discuss.,
https://doi.org/10.5194/cp-2018-27-AC2, 2018
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Interactive comment on "Inconsistencies between observed, reconstructed, and simulated precipitation over the British Isles during the last 350 years" *by* Oliver Bothe et al.

Oliver Bothe et al.

ol.bothe@gmail.com

Received and published: 16 July 2018

Dear referees, dear editor,

Once more, thank you for your candid and helpful judgment, comments, and suggestions.

Let us start with a preliminary note. We will follow the advice by the editorial office and are not going to prepare a revised version right now but rather wait for the editor's recommendations. While a structure of a potential new version is clear and presented below, our replies to the referees' comments depend on whether the point in question

will be included in a new manuscript.

Next we shortly repeat and slightly extend on our initial reply. Detailed responses to all comments follow below.

Intended changes in document:

Regarding the aims of the study we would like to point out once more that we a) aim to motivate the advantages in using the SPI for comparing various sources of information in paleoclimate research on precipitation and b) find for the case of a rather small domain on the British Isles that the sources of information lack consistency.

Our aim is not a comprehensive analysis of all available data for the British Isles. Our intention is to show for a small region the (in)consistencies between the various information sources. For the moment, we do not plan to include additional reconstructions or regions on the British Isles but rather to optimise our presentation of our chosen focus.

Your comments made it clear that we have to increase the clarity and improve the structure of the manuscript. Therefore we will rewrite abstract, introduction, methods section, and conclusions. This hopefully clarifies the motivation, the expectations, the aims, the methods, and the implications of our results. We will also improve the visual presentation. The results-section will require a profound revision, too, considering that we will likely add new analyses and remove some of the original analyses.

Regarding the results, the new version will concentrate on the analyses of the distributional precipitation properties, i.e., the SPI. We will add a comparison to further regional observational information sources. A manuscript asset, e.g., an appendix, is going to present shortly the Weibull distribution fits.

In turn, we will minimise the comparison between precipitation and temperature data and overall the analyses of temperature data. We aim also to regard the global simulations only in passing. Both parts will be moved to manuscript assets but these will be truly supplementary to the scope of our manuscript.

Detailed responses to all your comments follow below. Referee comments are put in red font and our replies in blue font. Intended changes in the document follow in default font.

0.1 Referee 1:

Overall, I found this paper to be very confusing to read and also not surprisingly hard to follow. Also in this form I don't think that it is worth publishing.

Author reply: Thank you for your honest evaluation. We aim to remedy your concerns in a new version.

Intended changes in document: We intend to rewrite abstract, introduction, methods section, and conclusions. This hopefully clarifies the motivation, the expectations, the aims, the methods, and the implications of our results. We will also improve the visual presentation.

I think this is because it is attempting to do too much in a single paper. I would be more interested in one where the observations and reconstructions are compared, then a separate paper or a separate part of a single paper, where the climate simulations are compared.

Author reply: We aim at this point to mostly remove the global models from the manuscript. The discussion of the regional simulation is going to be included in a new version of the manuscript.

Intended changes in document: The discussions and analyses of the PMIP3-ensemble is moved to a purely supplemental manuscript asset.

It seemed to me that every time there was something interesting, the discussion went on to a discussion of the models and initially a list of the models and all the necessary details about them in terms of refs/names/resolution/forcing etc. It would have been better if all this latter part was in a separate Appendix.

Author reply: We are not quite sure what you are referring to. However, descriptions of the PMIP3-ensemble will be removed from the main manuscript.

Intended changes in document: Remove descriptions of the PMIP3-ensemble.

The basic premise of the paper is that regional scale precipitation (here for England and Wales) should show some impact of external forcing, but it seems that not surprisingly that internal variability dominates. Maybe the authors should spend some more time looking at long observational series, and less time looking at climate model simulation output.

Author reply: Most of the analyses are on reconstructions and observations. We will add comparisons on additional Met Office data. We will discuss our expectations more. Indeed our basic premise is shortly described as: we need consilience of evidence from all sources of information to reach a robust understanding of past and future climate variability and climate changes. This also involves external forcings. Agreement about forced and unforced signals may signal consilience. Internal variability is likely to dominate the mean signal on regional scales, the SPI-transformation allows to compare quantiles of precipitation data more easily as well as other precipitation distribution properties.

Intended changes in document: We will add discussions on the data we use by comparing to additional data. These are the subdivisions of the Met Office Hadley Centre England-Wales precipitation data, i.e. the data for South West, South East, and Central England. Additionally, we use the instrumental precipitation data from Kew Gardens and Pode Hole. We will also specify our basic premises more clearly.

There are long precipitation records for the England and Wales region (including also the Central England Temperature series) and they have been analysed for a long time (i.e. there is a vast literature on analyses of these series, that this paper doesn't consider at all).

Author reply: We are not sure to which papers you refer specifically - or how they refer to the current analyses. We will however screen again respective databases in case we have overseen high quality and long data series over our region of interest and papers

discussing them.

Intended changes in document: Some additional references may be added.

Figure 2 clearly realizes the seasonal nature of the reconstructions plotting seasons such as MAMJJ and JJA.

Figure 1 though appears to look at annual averages for CET. So when in Figure 4 running correlations are shown for CET with precipitation observations, drought/precipitation reconstructions what season is being used. Is this CET for MAMJJ or JJA or is it annual CET? I couldn't decide what it is from the text or the captions. If it is CET annual then this is wrong. CET correlates with England and Wales rainfall in winter positively (warmer winters tend to be wetter) and inversely in summer (warmer summers tend to be drier). So relationships change with the season. Need to specify for every season what season is being used, otherwise people will assume annual like I did. These relationships ought to be captured by models, which is what I think you say, but this is buried in text somewhere else.

Author reply: All analyses use MAMJJ except when explicitly stated that it is JJA. We will clarify this point.

Intended changes in document: The results section will be more clearly formulated, Figure captions revised, and connections between text and Figures optimised. We aim to specify the season for every analyses described in the text.

This is another problem with the paper, that there appears little structure to it and the text doesn't flow in a logical order, and there is no summary at the end of the Introduction of what to expect in each of the subsequent sections.

Author reply: We will try to remedy this structural issues.

Intended changes in document: The structure will be revised. We do not plan to add a redundant summary of following contents at the end of the introduction.

Some specific points

1. SPI. Using a distribution for this is discussed. Whatever is chosen, the parameters ought to be compared.

Author reply: As clearly stated in the manuscript, we fit and use Weibull distributions. We will shortly present the parameters.

Intended changes in document: Manuscript assets are going to present the parameters of the Weibull distribution fits.

Tree-ring based reconstructions generally explain only a portion of the variance, so these are likely to have a lot less variance than the observations. This issue needs to be discussed.

Author reply: We will discuss this in more detail in the new version.

Intended changes in document: We are going to discuss the variance issue and how the original authors of the reconstructions rank this issue.

Comparison of series at SPI doesn't let the reader see the effects of the differences in explained variance.

Author reply: We are unsure on the point raised by the reviewer. The pure reconstruction series do not show this either in our original Figure 2.

Intended changes in document: As mentioned above, we will be more clear about the variance issue.

2. When you compare the reconstructions with England and Wales precipitation series in Figure 2, you seem to think that they will agree well. It is essential to look at how well SW England and also East Anglia compares with England and Wales. You can get the observed data here https://www.metoffice.gov.uk/climate/uk/summaries/datasets for periods since 1910. The correlations will not be as high as you imagine, partly because East Anglia is dry and also how the England and Wales series is put together.

See the brief discussion in Kendon and Hollis (2014).

Author reply: As you may have seen, we obtained data from the Met Office homepage. We will clarify these points. England-Wales does correlate very highly with South-West, South-East, and Central England on interannual time-scales and also for lower resolution data. The reconstructions are much less related to the observational sets on both scales. We do not see the relevance of Kendon and Hollis (2014) for this discussion.

Intended changes in document: We will include a more extensive comparison to the observational data series.

3. There are odd bits of discussion almost on every page. On p7, why do you thing the late-18 the century dip in temperatures is due to the Laki Eruption? The references don't look at CET and the eruption did not put material in the stratosphere. I've assumed you're referring to CET as the paper is about this region, but the Laki eruption has been postulated as causing cooler weather in central Europe in 1784 and 1785, but as said this isn't very convincing at all (compared to say the eruption of Tambora in 1815).

Author reply: We will clarify these points. Especially, we will discuss why we think the high latitude eruption of Laki could have an influence on European climate. You state yourself that the effect has been postulated, which by itself warrants inclusion of this date. However, we have to discuss in more depth how likely the eruption may have had an impact on European and British Isle temperatures in an extended spring season.

Intended changes in document: We will discuss the inclusion of this date if the new version includes this discussion.

4. You should state that all you expect with the models for this small a region is to get the precipitation amount right. You would need ensembles of runs to see if any of the low-frequency might agree. You seem to be expecting too much, or you need to explain

why you're expecting as much as you are.

Author reply: We will clarify our expectations. Indeed we absolutely do not expect to get the amount right. This is one reason why we think the SPI may help. If there is a forced response we may see it in the mean. Assuming the internal variability dominates the mean series, the SPI additionally allows to have a look at other properties of the precipitation distribution to see whether these may show a signal. Indeed, the suite of PMIP3-simulations and our regional simulation represent an ensemble.

Intended changes in document: We will more clearly discuss our expectations, why we think we do not need an ensemble of simulations, and why we in the end remove the global simulation ensemble.

5. As stated the text is difficult to follow. Much of p10 comes into this category. The bottom line of Figure 2 shows Weibull standard deviations, but what does this mean? Surely this is showing what I was talking about in 2? The whole running numbers are confusing. It doesn't help putting too many coloured series on the already quite small plots.

Author reply: We aim to provide a new version which is easier to follow. We will try to clarify all these points. The Weibull Standard deviation is the square root of the Weibull distribution variance as, e.g., presented at http://mathworld.wolfram.com/Variance.html (Weisstein, Eric W. "Variance." From MathWorld–A Wolfram Web Resource) or in a number of textbooks.

Running numbers allow displaying easily the changes in the distribution properties. We aim at improving the visualisations of the data.

Intended changes in document: Figures will be redrawn. Text will be clarified.

6. The opposite evolution in East Anglia and SW England might be correct (p11)? You need to look at the observations to check this. There is an outof-phase correlation between SE England and NW Scotland.

Author reply: We are not quite sure how NW Scotland relates to our analyses, but we have checked with the observationally derived series. We will further discuss this point in the new version. A comparison between more data series will be included, but it doesn't change the point here.

Intended changes in document: We will extend on the discussion.

7. If series (p12) have the order of one degree of freedom, then what are you doing showing them.

Author reply: The new version likely will not include this analysis.

Intended changes in document: The correlation analyses will be mostly or even completely absent from a new version.

Parts of this page are very difficult to read and follow.

Author reply: We will try to clarify this.

Intended changes in document: We will rewrite the results section.

8. No seasons are given with Figures 4 and 5.

Author reply: We will clarify the seasons throughout the manuscript. It is MAMJJ except when we additionally use JJA.

Intended changes in document: Captions will be clarified.

9. Trouet et al (2018) would have done better to have used the 300-year long instrumental records from the British Isles instead of going straight to tree-ring reconstructions. There are large variations across the British Isles with the size of the influence of the westerlies on precipitation amounts in the spring and summer. For example (p16) the NAO has no influence on East Anglian precipitation amounts in the winter half year. The NAO effect is much stronger on the western and northern areas of Britain, and it is mainly in the winter season. When you talk about spring/summer and the NAO are

talking about the same NAO as in winter? It would be useful to discuss how the North Atlantic Jet that Trouet et al (2018) talks about relates to the NAO, if it does?

Author reply: We will discuss the large scale circulation influence more extensively.

Intended changes in document: We will extend on the discussions of the large scale circulation.

10. P17 states that standardization of precipitation goes beyond comparing means and deviations. I'm not sure that you have shown anything other than just the means and SDs.

Author reply: Obviously, we disagree. We will clarify this point in the manuscript. Our analyses allows to compare the full distribution including measures that cannot be evaluated using the mean and the SD like the asymmetry of the distribution and its tails.

Intended changes in document: We will try to clarify the benefits of the SPI.

References Kendon M and D Hollis, 2014: How are UK rainfall-anomaly statistics calculated and does it matter? Weather 69, 37-39.

0.2 Referee 2:

While I think that this paper has merit and could provide interesting insight it is my view that it is not yet ready for publication. I encourage the authors to rethink the structure and layout of the paper and the key messages to be delivered. I think that such a paper would be welcomed by the field and of interest to the readers of the journal. But to reach a standard for publication significant work remains.

Author reply: Thank you. We are going to restructure the manuscript completely and clarify the key messages.

Intended changes in document: We will restructure the manuscript to provide more focussed information on our main points.

From the outset the specific aims of the paper are rather vague; the introduction section needs clearer structure. At the moment it jumps from one topic to the next without really unpacking where the state of knowledge it at in any aspect. The authors need to structure the introduction much more clearly, building the necessary context for the reader to understand what the aims are and the summary of information necessary to move to the next stage.

Author reply: We will more clearly structure the manuscript.

Intended changes in document: Introduction and also subsequent sections will be more clearly formulated.

If the focus is on the British Isles why just use the EWP series and not the Island of Ireland monthly series from 1711 or the Scottish regional series. I realise the latter is shorter, but to talk of the British Isles and not use the other available regional series is confusing. Murphy et al. (2018) cited in the introduction show that CET is also strongly correlated, at least at decadal scales with the Irish series.

Author reply: The focus is a small domain on the British Isles, not the whole of the

Isles.

Intended changes in document: We will clarify our spatial focus.

Why did the authors choose these tree ring reconstructions? To the best of my knowledge these are based on ring width reconstructions which have been shown to be less reliable for precipitation. Why not incorporate the oxygen isotope reconstructions done by Rinne et al. (2013) for southern England. Indeed in their discussion, if i recall correctly, they identify interesting points of departure from both EWP and Kew precipitation series for the summer months. Again in providing this suggestion as I am reading it is not clear what the time focus is of the paper – spring/early summer, spring?? The study design needs clearer thought, signposting and explanation.

Author reply: We will clarify the seasonal focus of the manuscript and the additional points you raise. We will argue for not using Rinne et al. in this context. Among other reasons: to our knowledge the data from Rinne et al. is not publicly available. The focus of the manuscript is an extended spring season. We will ensure that this becomes clear everywhere.

Intended changes in document: We will clarify our scope.

Regarding the selection of ensemble members from model reconstructions, why not use the entire ensemble? In the next paragraph it is noted that the selection is rather arbitrary and it is assumed that the domain sufficiently represents EWP domain. Some kind of table to help the reader interpret the different forcings used would be helpful.

Author reply: We are not quite sure what the reviewer is referring to but we will try to clarify this. We agree that the selection of the domain within a simulation is in a way arbitrary. We are going to move the analyses of the PMIP3-ensemble to a purely supplemental manuscript asset.

Intended changes in document: As far as this point is still relevant to a rewritten manuscript, we will try to clarify this. Analyses of the PMIP3-ensemble will be removed

from the main body of work.

The use of the SPI to investigate the 6.7 and 93.3 percentiles is a very stringent test of models and reconstructions is it not? The EWP is essentially a composite series and extremes are likely smoothed out. Also, is it a fair ask to expect climate model reconstructions to be able to represent these, especially if not employing a large ensemble? I am only asking out of curiosity here and would like to be informed of how stringent the comparison you are setting up is.

Author reply: We will discuss why we think the comparison of the distributions makes sense even for area average or composite series. By using distributions we essentially compare climate states which in theory should account for a part of the internal variability. Thus, assuming there is a common signal the evolution of the climatological properties could agree between data sets even without employing a large ensemble.

Intended changes in document: We are going to clarify the limitations and the stringency of our proposed method.

Any bias correction applied to the models? Does SPI negate this?

Author reply: No. We don't use statistically downscaled data. Bias-correction is not the scope.

Intended changes in document: We will clarify this.

Results presented in the methods section need to be moved.

Author reply: Will be changed.

Intended changes in document: Results from the methods section will be moved to later sections.

The paper is badly let down by plots that are very hard to decipher and methods applied that are not appropriately, or sometimes not at all, explained in the methods section.

Author reply: We will pay attention to clarify the visual presentation and the methods used.

Intended changes in document: We will take care to describe all methods and to present the results more clearly.

Fig 1 – no detail of the types of smoothing applied covered in the methods. What is a 'first impression' , not a scientific term. What CET time step is the smoothing applied to? Monthly or annual series. Why not plot as an ensemble rather than 11 sub plots? Line types in legend do not match the plots. Use of sunspot data is not covered in the data section so far as I recall.

Author reply: We will try to remedy all these points. We use a 51 point Hamming filter. We use the extended spring data here as well. We decided to use the 11 sub-plots since we regarded the ensemble plot to be even less visually helpful.

Intended changes in document: This Figure or a similar representation is likely going to be moved to a purely supplementary manuscript asset. Discussions of the sunspots will either be added or the data will be completely removed from the manuscript.

A table detailing the various data sources compiled is badly needed.

Author reply: We will present the used data in a clearer manner.

Intended changes in document: We will present the used data in a clearer manner.

The use of differing periods is confusing, how can this be comparative – which is the primary aim of the paper.

Author reply: We will try to be more clear in our thinking on how to compare the used data sets. However, we are unsure to what part of the manuscript this comments precisely relates.

Intended changes in document: The methods section will give more details on the comparisons.

Please think about presenting results in a clearer way. I literally spent hours trying to figure out what the figures were showing and in many aspects am no clearer.

Author reply: Thank you for spending so much time on the manuscript. We aim to clarify the presentation including a clearer outline of the spatial, methodological and dynamical considerations of the manuscript.

Intended changes in document: The new methods section will clearer spell out what is shown later, and Figures will be optimised.

There needs to be a more systematic approach to this work in terms of presentation and some sub sectioning in the results and discussion to help the reader.

Author reply: We will try to lead the reader more clearly through our thinking.

Intended changes in document: We will try to structure the results-section more clearly and to more systematically direct the reader through the manuscript.

The title of the paper concerns precipitation. It is confusing to start the results off with temperature.

Author reply: Discussions of temperature will be minimised in a new version and not start the results.

Intended changes in document: The results section will be restructured.

I find it next to impossible to interpret the caption of Figure 2.

Author reply: We will clarify the presentation of Figures and captions.

Intended changes in document: Figure captions will be clarified.

It is difficult to comment in much depth on the nature of the results and the points made in discussion and conclusion given how difficult it is to decipher what was done.

Authors need to revise the structure of the paper to systematically consider the inconsistencies of interest.

Author reply: We will try to make our points more clearly in a new version.

Intended changes in document: A rewrite of the manuscript is necessary.

0.3 Referee 3:

Summary: The manuscript involves a comparison of climate model simulations with an ensemble of global and one regional model to long observationally-based records and two paleoclimate reconstructions. Little consistency is found between time histories of these records, suggestive of a large role for internal atmosphere-ocean variability. Importantly, while there is little agreement between the characteristics of the model simulations and the observationally-based records, these differences do not appear to be systematic across models and cannot be explicitly linked to model bias. Likewise, there appears to be even less agreement between the characteristics of the observationally based records and the reconstructions. Together this work is consistent with mounting evidence that regional hydroclimate is largely "unforced".

General Remarks: While the manuscript is interesting and highlights some important results, it is at times unclear what should be taken away from the results. This is, in part, an issue with the introduction and a refocused introduction that clearly describes the motivations and goals of the study would greatly improve the manuscript. Below are a number of specific and more general comments.

Author reply: A new version will clarify the introduction not only with respect to the motivation and the conclusions but also related to the general focus and intention and peculiarities of our approach in comparing different sources of information.

Intended changes in document: The complete manuscript is going to be restructured.

Page 1, Line 8: and in the standard deviations seems a weird statement.

Author reply: To be changed.

Intended changes in document: We will modify the abstract.

Page 1, Line 18: add "of" before "whether".

Author reply: Will be changed.

Intended changes in document: Will be changed

Page 1, Line 19: what is meant by requires consistency?

Author reply: We will clarify our idea of requiring consistency.

Intended changes in document: Introduction and discussions are going to be more explicit about what we mean by consistency.

Page 1, Line 21: suggest changing to “over approximately the last 350 years”.

Author reply: Will be modified.

Intended changes in document: Will be modified.

Page 2, Line 2: suggest removing “in particular”.

Author reply: We will rephrase the sentence.

Intended changes in document: Will be rephrased.

Page 2, Line 6: change “base” to “basis”.

Author reply: Will be changed.

Intended changes in document: We will change the sentence.

Page 2, Line 10: change “compare directly” to “directly compare”.

Author reply: Will be changed.

Intended changes in document: Will be changed.

Page 2, Line 12: Cooper and Wilson et al. are the reconstructions. I would be careful here and throughout with the semantics of “data”.

Author reply: We will try to be clear in how we refer to the various

sources of information. However regarding the longstanding discussions on what may be named “data”, the Wiktionary writes, slightly paraphrased, at https://en.wiktionary.org/wiki/dataEnglish: data: a) Information, especially in a scientific or computational context, or with the implication that it is organized. b) Recorded observations that are usually presented in a structured format. c) A representation of facts or ideas in a formalized manner capable of being communicated or manipulated by some process. Data in the context of our writing is generally any set of information.

Intended changes in document: We will carefully consider how we describe the various sets of information.

Page 2, Line 16: You argued in the paragraph above that you do not want to use gridded reconstructions. I understand that this paragraph is addressing a new issue but the reference to the OWDA thus seems unusual here. In general, this paragraph does not seem necessary. I might instead start at the beginning of the next paragraph and add a statement at the end of that first sentence saying that you are doing the standardization to make the reconstructions directly comparable to SPI.

Author reply: We will try to more clearly justify the choice of method and data.

Intended changes in document: We will rephrase the introduction to ensure a logic reading.

Page 2, Line 24: Suggest changing “their data” to “the utilized archives”.

Author reply: We will rephrase the sentence.

Intended changes in document: Will be phrased differently.

General comment: A lot of the above reads much more like a methods section than an introduction. I suppose this is more of a personal preference but the paper might be more impactful with a standalone introduction that does not include this methodological information.

Author reply: We will try to better separate introduction and methods.

Intended changes in document: We will take care to clearly distinguish between introductory comments and the description of the methods and the data..

Page 2, Line 24: The sentence about Murphy et al. (2018) feels out of place. I would try to tie this into the paragraph above or remove it.

Author reply: We will try better to embed the point of Murphy et al. (2018).

Intended changes in document: Introduction will be rephrased.

Page 2, Line 28: Suggest removing "than in periods that are more recent".

Author reply: We will restructure the sentence.

Intended changes in document: We will phrase the sentence more clearly.

Page 2, Line 29: Suggest splitting the sentence after the Maunder Minimum dates. I would then reword as: "Instead, they generally start around the late 18th century, when sunspot numbers indicate a period of relatively strong solar activity (Clette et al., 2014), and thus also include the transition. . ."

Author reply: We will clarify the point.

Intended changes in document: The paragraph will be modified.

Page 2, Line 35: Suggest changing "in European subdomains" to "across Europe".

Author reply: We will modify the sentence.

Intended changes in document: We will make the point more clearly.

Page 3, Line 1: Change "extend" to "extent".

Author reply: Will be changed.

Intended changes in document: Will be changed.

Page 3, Line 10: This sentence is long and the second half I had trouble understanding. Perhaps you could split this up into two sentences and expand on the point that you are trying to make in the second half of the sentence.

Author reply: We will try to clarify the point.

Intended changes in document: The paragraph will be clarified.

Page 3, Line 20: Suggest "using the global model ECHO-G for boundary conditions" instead of "externally forced". I am also not sure what this part of the sentence means: "and reconstructions over larger regional domains."

Author reply: We will clarify the sentence.

Intended changes in document: We will make the point more clearly.

Page 4, Line 1: Suggest changing "and the simulation data representing" to "and simulations that often represent".

Author reply: We will adapt the sentence.

Intended changes in document: Will be changed

Page 4, Line 2: Suggest changing "evaluation" to "comparison".

Author reply: Will be changed

Intended changes in document: Will be changed.

Page 4, Line 17: Change "allows comparing" to "allows for the comparison of".

Author reply: Will be changed

Intended changes in document: Will be changed.

Page 4, Line 19: Change "allows evaluating and comparing" to "allows for the evaluation and comparison of".

Author reply: Will be changed.

Intended changes in document: We will rephrase the sentence.

Page 4, Line 22: Suggest changing “extends the available metric for assessing the agreement in” to “allows for the rigorous comparison of”.

Author reply: We will try to discuss this point more clearly.

Intended changes in document: We will extend on this point in a new version.

Page 4, Line 23: Suggest changing “not only for periods without but also with” to “for periods both with and without”.

Author reply: We are going to change the sentence.

Intended changes in document: Will be changed.

General comments on introduction: I am unsure about the relevance of short-term (decadal) relationships between temperature and precipitation with those expected as a result of climate change (first two sentences of the introduction). The relationship between hydroclimate and temperature at the end of the 21st century in climate models is largely due to evaporative demand, which has a first order impact on water storage but not necessarily on precipitation. These changes are also very large in magnitude, and co-occurring with large magnitude changes in plant physiology, making deeper-time paleoclimate comparisons more appropriate for evaluating climate models (e.g., Scheff et al., J. Clim., 2016). I do not think this precludes such analyses being useful, I am just unsure of using the relationship between temperature and precipitation with an eye towards climate change as the motivation.

Author reply: We are going to adapt the motivation to address this point and to provide a more focussed impetus for our study. The link between temperature and precipitation is more complex, and not only restricted to long time scales. It may be modulated even at interannual timescales by other processes, for instance, through the link between

temperature and cloud cloud cover during the extended summer season. Thus, an analysis of the covariability between temperature and precipitation even at interannual and decacdal time scales serves as a validation of both reconstructed variables on the one hand, and of the corresponding link between these two variables in climate models on the other hand.

Intended changes in document: The motivation will be rephrased.

I would be careful with the semantics of the word data to make sure that things are as clear as possible. Likewise, I would refer to reconstructions, observations and simulations each with a single consistent term. This applies to the entire manuscript.

Author reply: We will try to be consistent in the descriptions of the various sources of information.

Intended changes in document: As mentioned above, we will take care to be clear in our use of the term data and its application to the various sources of information.

The introduction bounces around a lot, with quite a bit of methodology (see general comment above). I think that as cast it will leave the reader uncertain about the motivations and goals of the study. I suggest that the authors revisit the introduction with an eye towards clarity.

Author reply: We are going to try to motivate our study more clearly and to provide the reader with a better picture of from where we start and where we try to go.

Intended changes in document: The introduction will be reformulated.

I made an effort to make grammatical edits in the introduction but likely missed some. I will not be able to make this effort in subsequent sections but suggest that the authors revisit the manuscript with an eye towards grammar and syntax.

Author reply: We are going to try to improve the language, once more.

Intended changes in document: We are going to improve the language.

It might be worth explicitly outlining how what you are doing here is different from Gómez-Navarro et al. (2015). Along with what is described the methods there would appear to be quite a bit of overlap.

Author reply: To be clear, we are co-authors on GN15. GN15 look at a regional simulation and gridded reconstruction over the European domain. They, among other things, compare both for a variety of regional sub-domains and a number of different datasets. They do not consider the small regional scale, they do not consider the SPI, they always have the spatial reconstruction step.

Intended changes in document: We will clarify the difference between Gómez-Navarro et al. (2015) and our manuscript.

Page 4, Line 28: Change to "in the form".

Author reply: We will modify the sentence.

Intended changes in document: Will be modified.

Page 5, Line 15: Suggest adding "In particular," at the start of this sentence to link it to the previous sentence. Suggest also changing "different means" to "systematic differences in the values of".

Author reply: We will adapt the paragraph

Intended changes in document: We will change the paragraph.

Page 5, Line 16: Suggest "While model-biases may also contribute to these differences,. . ." and change "bias" to "source of differences".

Author reply: We are going to adapt the paragraph.

Intended changes in document: The paragraph will be clarified.

Page 5, Line 17: I doubt it matters but why the different domain here?

Author reply: The domains for CET and EWP differ, thus we also adapt different model

domains. However, a new version will have a smaller role for the temperature data.

Intended changes in document: We will remove much of the temperature discussion from the manuscript but also discuss the different domains more clearly if necessary.

Page 5, Line 30: Change "to include" to "the inclusion of".

Author reply: Will be changed.

Intended changes in document: To be changed.

Page 6, Line 5: Change "allows to compare" to "allows for the comparison of".

Author reply: Will be changed.

Intended changes in document: To be changed

Page 6, Line 19: Change "allows considering the changing amount of precipitation" to "allows for a robust quantification of changes in precipitation amounts between subsequent periods, for instance ".

Author reply: We will clarify this paragraph.

Intended changes in document: Will be clarified.

Page 7, Line 2: Remove "just".

Author reply: Will be changed.

Intended changes in document: To be changed.

Page 7, Line 3: Add "the" before "time series".

Author reply: Will be changed.

Intended changes in document: To be changed.

General comments on methods: The half-degree simulations are course resolution for a regional climate model. At least one of the last millennium simulations analyzed is one degree (CCSM4), how much added information do we expect from a regional simulation at this course resolution and what physical processes is it capturing to provide that information?

Author reply: We will comment on this. See, for example, the most recent papers by Ludwig et al. (2018) and Sørland et al. (2018).

Intended changes in document: We will more clearly discuss the benefit of even a slight increase in resolution and why a regional simulation adds more benefits than just an increased resolution.

Page 7, Line 13: Change “tentative” to “qualitative”.

Author reply: Will be changed.

Intended changes in document: Will be changed.

Page 7, Line 20: Suggest change the last sentence to “This is likely to also impact our analyses of precipitation”.

Author reply: We may modify the sentence.

Intended changes in document: We will clarify this paragraph.

Page 7, Line 32: What is the European domain?

Author reply: We will detail the domain.

Intended changes in document: In case it is still relevant in a new version, we will be specific about this larger European domain.

Page 8, Line 2: Suggest removing the first sentence.

Author reply: We are going to restructure the description of our results

Intended changes in document: The results section is going to be rephrased and restructured.

Page 8, Line 5: Suggest changing “representations” to “time series”.

Author reply: Will be changed.

Intended changes in document: To be changed.

Page 8, Line 7: Suggest removing “but the Southern-Central England data enters it later”.

Author reply: We will clarify the description of the results.

Intended changes in document: The results will be clarified.

Figure 2, caption: Why call the Southern-Central England record SW England in the legend?

Author reply: Will be changed. Thank you for pointing out this oversight.

Intended changes in document: To be changed.

Page 10, Line 23: Change “allows evaluating” to “allows for the evaluation of”.

Author reply: We will clarify the sentence.

Intended changes in document: This will be clarified.

Page 10, Line 24: Change “gliding” to “sliding”.

Author reply: Will be changed.

Intended changes in document: To be changed.

Page 10, Line 25: Suggest removing “partially”.

Author reply: Will be removed.

Intended changes in document: To be removed.

Page 10, Line 27: Change sentence to read “The moving window transformations show the percentiles represented by a given amount of precipitation over time (Figure 3).“

Author reply: We are going to clarify the procedure.

Intended changes in document: This part of the manuscript will be clarified.

Page 12, Line 1: Suggest changing “We pointed above at” to “In the previous sections we described”.

Author reply: We are going to modify the sentence in question.

Intended changes in document: This part will be clarified.

Page 12, Line 6: Suggest changing “gliding” to “sliding”.

Author reply: Will be changed.

Intended changes in document: To be changed.

Page 12, Line 11: Suggest combining these two sentences.

Author reply: We are going to make the point more clearly.

Intended changes in document: We are going to change this paragraph.

Page 12, Line 12: Suggest changing “Considering” to “In”.

Author reply: We are going to modify the sentence.

Intended changes in document: To be changed.

Page 12, Line 15: Suggest removing “correlation”.

Author reply: Will be removed.

Intended changes in document: To be removed

Page 12, Line 20: Suggest changing “highly” to “strongly”.

Author reply: Will be changed.

Intended changes in document: Will be changed.

Page 12, Line 21: Why “CET” here and not elsewhere?

Author reply: We are going to be more consistent in the use of abbreviations.

Intended changes in document: The new version will be consistent in use or avoidance of abbreviations.

Page 12, Line 31: Change “very low frequent variability” to “low frequency variability”.

Author reply: Will be changed.

Intended changes in document: To be changed.

Page 15, Line 8: Again why the use of “CET” here and not elsewhere?

Author reply: We are going to be more consistent in the use of abbreviations.

Intended changes in document: A new version is going to be consistent in use or absence of CET, EWP, and other abbreviations.

Page 15, Line 15: Why just atmospheric circulation when coupled variability can also do this?

Author reply: Indeed. We will change this and discuss more extensively factors influencing the regional domain.

Intended changes in document: We will clarify this discussion.

Page 15, Line 24: I found this paragraph difficult to understand. The final sentence is seemingly important but I was unclear on what it means. Likewise, I would clarify what is meant by unfortunate earlier in the paragraph.

Author reply: We are going to clarify our thinking on regional climate variability, natural forcing, the relation between temperature and precipitation, and the precipitation distributions.

Intended changes in document: A new version will discuss this more clearly.

Page 16, Line 7: Suggest changing “appears” to “is”.

Author reply: Will be changed

Intended changes in document: Will be changed.

Page 16, Line 23: While this is true, it is unclear how it relates to the other discussion.

Author reply: We are going to better connect the discussion on changing teleconnections to the discussions on internal variability and the representativeness of data sources.

Intended changes in document: Discussions of a new version will be more clear in this discussion.

Page 17, Line 19L Change “source” to “sources”

Author reply: Will be changed

Intended changes in document: To be changed.

A note is in place on potential added references. There are a number of topics, which may need discussing additional references.

First, there is the SPI. We have not yet decided which of the previous studies using the SPI in paleoclimatology are essential for our argumentation. Candidates include Domínguez-Castro et al. (2008, doi:10.1016/j.gloplacha.2008.06.002) Machado et al. (2011, doi:10.1016/j.jaridenv.2011.02.002), the SPI use by Lehner et al. (2012, see original references), Seftigen et al. (2013, doi:10.1002/joc.3592), Yadav et al. (2015, doi:10.1016/j.quascirev.2015.04.003), and Tejedor et al. (2016, doi:10.1007/s00484-015-1033-7). These, however, mainly deal with the SPI as original reconstruction target.

Second, as we noted above, we have to discuss why we think the used regional climate model has indeed a chance to improve on the representation compared to the PMIP3-ensemble. Recent publications by Ludwig et al. (2018, doi:10.1111/nyas.13865, Sørland et al. (2018, doi:10.1088/1748-9326/aacc77), and Pinto et al. (2018, doi:10.1002/joc.5666) allow to make this point. These may also become relevant in discussing how our work differs from Gómez-Navarro et al. (2015).

Third, while we in principle think that our references for contextualising regional climate variability and the large scale are sufficient, we may include additional discussions on the relation between the large scale climate dynamics and precipitation (e.g., Jones et al., 1993; Mayes, 1996; Wilby et al., 1997; Osborn and Jones, 2000; Murphy and Washington, 2001; Wedgbrow et al., 2002; Kingston et al., 2006; Lavers et al., 2010;).

Fourth, there remains the question, how much of the literature on the British observational datasets is relevant to the discussions. Our initial assessment was that the main references for the datasets are enough. Possibly, additional references will be added (e.g., Wigley and Jones, 1987; Gregory et al., 1991; Jones and Conway, 1997; Kilsby et al., 1998; Osborn et al., 2000; Croxton et al., 2006; Marsh et al., 2007; Simpson and Jones, 2012; Simpson and Jones, 2014).

It remains to be seen to what extent discussing the issues of the used and not considered reconstructions requires additional references.

Once more, thank you for your help.

On behalf of the authors

Yours sincerely

Oliver Bothe

Interactive comment on Clim. Past Discuss., https://doi.org/10.5194/cp-2018-27, 2018.

List of relevant changes to the manuscript:

Overall manuscript:
- restructured
- title slightly changed

Abstract:
- partially rewritten

Introduction:
- restructured
- partially rewritten
- Discussions on uncertainty of comparison studies extended
- Discussions on SPI extended
- Discussions on all types of data extended, i.e. on simulations, reconstructions, and observations
- Discussions on consistency extended
- Discussions on our expectations extended

Data:
- rewritten
- data table added
- Discussion of choice of parameter, domain, data-types, and data-sources extended

Methods:
- rewritten
- Discussion of SPI extended
- Discussion of Smoothing added

Results:
- Figures redone
- PMIP3 removed to supplementary asset
- Plot of precipitation added
- more instrumental data included
- observational indices for subdivisions of the England-Wales precipitation newly included
- Correlation analyses added
- rewritten
- relation between temperature and precipitation minimised

Discussions:
- restructured
- rewritten
- Discussion of SPI extended
- Discussion of data extended
- Discussion of additional data added

- Discussion of approach extended
- Discussion of results extended
- Discussion of additional results added
- Discussion on internal variability extended
- Discussion on dynamics extended

Conclusions:

- slightly rewritten

Appendices:

- partially rewritten
- Distributional parameter plots added

Supplement:

- added
- additional Figures
- additional analyses

Inconsistencies between observed, reconstructed, and simulated precipitation ~~over the British Isles during~~ indices for England since the ~~last 350 years~~year 1650 CE

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Abstract. The scarcity of long instrumental records, uncertainty in reconstructions, and insufficient skill in model simulations hamper assessing how regional precipitation changed over past centuries. Here, we use standardised precipitation data to compare ~~global and regional climate simulations and reconstructions~~a regional climate simulation, reconstructions, and long observational records of seasonal (March to July) mean precipitation in England and Wales over the past 350 years. ~~The effect of the external forcing on the precipitation records appears very weak. Internal variability dominates all records. Even the relatively strong exogenous forcing history of~~ The Standardized Precipitation Index is a valuable tool for bridging part of the problems in assessing agreement and disagreement between the different sources of information. We assess the agreement in the ~~late 18th and early 19th century shows only little effect in synchronizing the different records. Multi-model simulations do not agree on the changes over this period. Precipitation estimates are also~~ temporal evolution of percentiles of the precipitation distributions. These evolutions are not consistent among reconstructions, ~~simulations~~a regional simulation, and instrumental observations ~~regarding the probability distributions' changes in the quantiles~~ for severe and extreme dry ~~or wet conditionsand in the standard deviations.~~

~~We have also investigated the possible link between precipitation and temperature variations in the various data sets . This relationship is also not consistent across the data sets. Thus, one cannot reach any clear conclusions about precipitation changes in warmer or colder background climates during the past centuries.~~

and wet conditions. The lack of consistent relations between the different data sets may be due to the dominance of internal climate variability over the purely natural exogenous forcing conditions on multi-decadal time-scales. This, in turn, questions our ability to make dynamical inferences about hydroclimate variability for small regions. However, it is encouraging that there is still some agreement between a regional simulation and observational indices. Our results emphasize the complexity of ~~changes in the hydroclimate~~ hydroclimate changes during the most recent historical period and stress the necessity of a thorough understanding of the processes affecting forced and unforced precipitation variability.

1 Introduction

Confidence in future climate projections of, e.g., ~~extreme~~ drought and wetness conditions requires understanding of past climate and hydroclimate variability and its drivers (e.g. Schmidt et al., 2014a). ~~In the case of the hydroclimate, a specific interest is on~~

the question whether there is a link between regional precipitation changes and the temperature background conditions. In turn, understanding past changes requires consistency among estimates from early instrumental observations, paleo-reconstructions from environmental archives, and climate simulations (Bunde et al., 2013). Here we explore the different data sources focusing on precipitation changes over the British Isles over the last about 350 years with the aim to compare the variations in the data and to test potential links between precipitation and temperature variability in these data sources.

Specifically we set out to test the consistency of these data sets not only in the mean but also in further statistical properties. Therefore, we consider standardised precipitation data by computing the Standardized Precipitation Index (SPI; McKee et al., 1993). We further shortly explore the interrelation between the regional temperature and the statistics of the precipitation data.

Consilience of evidence increases the robustness of estimates of future changes , which for precipitation Focussing on the hydroclimate, estimates of past and future changes are still highly uncertain in particular for precipitation at regional scales. Indeed, our understanding of internal, naturally forced, and anthropogenically forced variability is weaker for precipitation than for temperature due to the more complex controls on precipitation variability (e.g. Zhang et al., 2007; Hoerling et al., 2009; Iles et al., 2013; Fischer et al., 2014) and the more local-scale nature of precipitation-processes.

Long observationally based records (e.g., the England-Wales precipitation data; Alexander and Jones, 2000) allow us to assess how the statistics of precipitation have changed over the last couple of centuries. These data also provide the base for evaluating how state-of-the art global and regional climate model simulations and reconstructions compare in domains close to the available observations.

Climatic changes affect humans and the environment most on the local and regional scale. Therefore, we focus on precipitation data from small domains, Consistency among estimates from early instrumental observations, paleo-reconstructions from environmental archives (i.e.we compare directly local to regional domain precipitation reconstructions. We choose two small regional domains on the British Isles because long instrumental temperature data, cf., the Central England Temperature series, is available for comparison. We use the data by Cooper et al. (2013) and Wilson et al. (2013) for East Anglia and Southern-Central England, respectively. This is despite the fact that continental domain gridded precipitation reconstructions exist (e.g. Pauling et al., 2006; Casty et al., 2007; Franke et al., 2017). We only use the single time-series data instead of the gridded products to avoid the possibly spurious non-climatic variance introduced by reconstruction techniques.

Reconstructions of drought indices like the Palmer Drought Severity Index (PDSI) exist as gridded products for various regions of the world including Europe (The Old World Drought Atlas, Cook et al., 2015). These products allow assessing paleo-hydroclimate in simulations (Smerdon et al., 2015). However, precipitation is a more tangible variable than drought indicators like the PDSI. Indeed the UK drought portal () relies on the Standardized Precipitation Index (SPI McKee et al., 1993) instead of the PDSI, and there are recommendations to use the SPI in operational monitoring of meteorological drought (e.g. Hayes et al., 2011).

Hence, we compare the precipitation reconstructions directly though in standardised form to the simulations and observational series. We focus on an extended spring season (MAMJJ) since Cooper et al. (2013) and Wilson et al. (2013) identified this as the season their data are sensitive to for their reconstructions of precipitation. Murphy et al. (2018) emphasize the importance of comparing simulations and long local to regional historical weather records in describing their monthly 305-year long precipitation record for Ireland.

A period of interest in the recent past coincides with the Late Maunder Minimum when climate conditions differed considerably more from average 20th century conditions than in periods that are more recent. However, long observational records usually do not cover the Late Maunder Minimum (~1645 , paleo-observations), and climate simulations supports our understanding of past changes. Here, consistency among estimates simply means that various sources of information do not contradict each other. Consistency is a weaker requirement than to ~1715 CE) but they still generally start around the late 18th century, when sunspot numbers indicate a period of relatively strong solar activity (Clette et al., 2014). Furthermore, these data also include the transition into the early 19th century with the reduction in solar activity during the Dalton Minimum. A number of strong tropical volcanic eruptions also occurred during this period, i.e. in ~1809 (unknown location), 1815 (Tambora), and 1835 (Cosigüina) (e.g., Schmidt et al., 2011).

In this period climate reconstructions based on indirect indicators show notable anomalies in temperature and /or precipitation in European subdomains (compare data from Luterbacher et al., 2001, 2002, 2004; Xoplaki et al., 2005; Dobrovolný et al., 2010; Pauling e These climatic excursions are to a lesser extend also present in observations for Central England (Parker et al., 1992). While global climate simulations also indicate similar temperature tendencies (Masson-Delmotte et al., 2013), precipitation tendencies are less clear. expect consilience, i.e., it is weaker than requiring that the evidence from the different data sets converges. Despite being a more liberal metric, consistency is an appropriate measure in view of the multiple sources of uncertainty in inferring past hydroclimate and precipitation variability.

Paleo-reconstructions of the recent past have made notable progress both in the spatial coverage and in the quality of the reconstructions by incorporating so far unexplored data sources. Küttel et al. (2010), for example, highlight the importance of ship-based observations recorded in log books for reconstructing large-scale fields. Initiatives like or ACRE (Atmospheric Circulation Reconstructions over the Earth,) are invaluable for such efforts and also aid reanalysis projects like the twentieth century reanalysis (Compo et al., 2011), the reanalysis of global fields for the period 1600 to 2005 by Franke et al. (2017), or the last millennium climate reanalysis (Hakim et al., 2016)Here, we explore consistency and inconsistency of observations, reconstructions, and simulations for one small region and focusing only on precipitation changes. Specifically we set out to study the consistency in the statistical properties of precipitation distributions in these sources of information.

Common problems in comparing precipitation simulated with climate models and target data relate Comparing precipitation among different data sources poses various challenges. Problems relate not only to pronounced biases in the simulated precipitation, especially derived from raw global models, and to differences in representation or, in the case of data fields, the grid resolution. In the context of long observational time-series, data inhomogenities time series, data inhomogeneities due to changes in instrumentation, measuring techniques, and changes in locations can further influence estimates of longer-term trends (Böhm et al., 2010). Another challenge in comparing models and observations is the quality of the simulated precipitation, which still strongly depends on the parameterisations implemented.Precipitation, especially convective precipitation events, are still sub-grid processes, even within regional climate models.Concentrating on accumulated amounts on seasonal time-scales and their long-term changes, however, allows a more robust comparison of simulated precipitationto observed and reconstructed data.

Regarding regional climate modelling, Gómez-Navarro et al. (2015) evaluate a regional simulation with the model MM5 and externally forced by the global model ECHO-G and reconstructions over larger regional domains. They conclude that the numerical downscaling with a regional climate simulation indeed improves the representation compared to general circulation models, and reconstructions and simulations do not generally lack consistency. However, they emphasize model shortcomings and the lack of agreement in representations of extreme climate anomalies. On the side of the reconstructions, Gómez-Navarro et al. (2015) s the inconsistencies between the reconstructions of different parameters (i.e., temperature, precipitation, and sea level pressure).

The authors compare their simulations to the precipitation reconstructions of Pauling et al. (2006) for Western Europe. The reconstruction uses a set of dendroclimatological and other natural proxies and documentary information. Gómez-Navarro et al. (2015) find rather good agreement in (Frank et al., 2007; Wilson et al., 2005; Böhm et al., 2010). Reconstructions likely represent only part of the variability spectrum of, e.g., precipitation, dependent on the strength of the climatic signal in the original data and on further shortcomings of the evolution of median precipitation amounts between the reconstruction and their regional simulation for a domain including the British Isles and Ireland for the summer season. The interquartile ranges evolve similarly, too, over much of their study period from 1500 to 2000CE in summer. However, the agreement is much weaker for the spring seasonunderlying paleo-observations (compare discussions by PAGES Hydro2k Consortium, 2017). The PAGES Hydro2k Consortium (20 in more detail the problems in comparing hydroclimatic variables between reconstructions and simulations.

The PAGES Hydro2k Consortium (2017) developed recommendations for the comparison of hydroclimate data from representations in simulations and paleo-observations, emphasizing the uncertainties of both sources of dataestimates from both sources. They stress the complementary nature of simulated and environmental information. Their recommendations target the validity and appropriateness of a robust comparison. For example, we have to ensure that the data used for a comparison Estimates have to represent the same parameters on related spatial and temporal scales. The Only then, a comparison can be valid. We need appropriate methods to bridge the gap between the local or regional reconstruction and the simulation data representing larger scale aggregates remains one of the major hindrances in the evaluation of simulations and reconstructions. Therefore, comparisons have to use appropriate methods bridging this gapoutput that represents aggregates over larger spatial scales. Proxy system models (Evans et al., 2013; PAGES Hydro2k Consortium, 2017) are one means to achieve this (Evans et al., 2013; PAGES Hydro2k We argue that the standardisation of precipitation data is another estimates is a simple means to compare the statistical properties of hydroclimate hydroclimatic parameters in simulations and paleo-observations complementing the current suite of statistical diagnostics for model-data comparisons. It is of value for periods with and without comprehensive sets of climate and weather observations.

The high amount of internal variability on local and regional scales complicates the comparison among different data sources when studying small regions. On the other hand, we can assume that in the case of the British Isles the large-scale influence of the storm track over the North Atlantic is of particular importance for controlling precipitation variability (e.g., Bengtsson et al., 2006). Blackburn et al. (2008) detail the large-scale influences, e.g. , the wave-train pattern on the jet stream, on the flooding events in the UK in 2007. Trouet et al. (2018) link the August North Atlantic Jet variability to extreme weather events on the British Isles over the last 300 years . Studying the large-scale dynamics related to past precipitationvariability on Transforming precipitation estimates to the Standardized Precipitation Index (SPI; McKee et al., 1993) facilitates the comparison of different sources of information on precipitation in view of the mentioned challenges. It provides a common basis for comparisons between different locations, periods or seasons. The core of the SPI calculation is the fit of a distribution function to the precipitation estimates.

Previous usage of the SPI in paleoclimatology generally focussed on the index series (compare, e.g., Domínguez-Castro et al., 2008; Seft did not consider further information available through the transformation. We apply the SPI over moving windows of 51 years to study variations in the properties of precipitation distributions on multi-decadal time-scales. We concentrate on a regional domain where all sources of data, i.e., observations, reconstructions, and simulations are available. By applying the SPI-transformation over moving windows, we are able to evaluate and compare percentiles of the estimates as well as the moments of the distributions and the temporal changes of these distributional properties. We are essentially comparing sequences of climatologies.

Long observationally based records allow us to assess how the statistics of observed precipitation have changed over the last couple of centuries. They, in turn, provide the basis for evaluating how state-of-the art regional or global climate model simulations and reconstructions for the Common Era (CE) compare in domains co-located with the available observations. We choose southern Great Britain as our domain of interest since there are precipitation observations available in form of the England-Wales precipitation data set (Alexander and Jones, 2000, for the period 1766 CE to present), its subdivisions, and instrumental records for Oxford (cf. Radcliffe), Pode Hole and Kew Gardens. The instrumental records start in 1767 CE, 1726 CE, and 1697 CE, respectively.

A number of precipitation reconstructions are available for the South of Great Britain. We choose the millennium-long tree-ring based data by Cooper et al. (2013) and Wilson et al. (2013) for East Anglia and Southern-Central England, respectively. We focus on an extended spring season (MAMJJ). The next section discusses our decision to concentrate on this data instead of the $\delta^{18}O$-based scaling approaches by Young et al. (2015, covering the period 1766 to present) and Rinne et al. (2013, reconstructed values

Regional simulations for the last 500 to 2000 years are rare. Among studies on these, Gómez-Navarro et al. (2013) describe a regional simulation with the model MM5 for Europe. Gómez-Navarro et al. (2015) compare this simulation to reconstructions for various parameters over larger regional domains within Europe. For precipitation, they compare the simulation to the gridded precipitation reconstructions of Pauling et al. (2006) for Western Europe, which is based on a set of dendroclimatological and other natural proxies and documentary information. Gómez-Navarro et al. (2015) find rather good agreement in the evolution of median precipitation amounts between the reconstruction and their regional simulation for a domain including the British Isles ~~also benefits from recent reconstructions of~~ and Ireland for the summer season. The agreement is much weaker for the spring season. They also emphasize model shortcomings and the lack of agreement in the representations of extreme climate anomalies. On the side of the reconstructions, Gómez-Navarro et al. (2015) stress the inconsistencies among the reconstructions of different parameters (i.e., temperature, precipitation, and sea level pressure~~fields (e.g. Küttel et al., 2010; Franke et al., 2017). Indeed, the storm track is sensitive to solar (e.g., Ineson et al., 2015) and volcanic forcing (e.g., Fischer et al., 2007; Trouet et al., 2018). Since our~~).

Here, we compare observations and paleo-observations with each other. We additionally compare them to output from a regional simulation with the model CCLM for the European domain over the period 1645 to 1999 CE (compare Gómez-Navarro et al., 2014 Our comparison differs from Gómez-Navarro et al. (2015) by using a different regional model, focussing on a smaller region, and by using regional time series reconstructions instead of deriving records from gridded products. Moreover, our general focus is on precipitation~~statistics rather than precipitation dynamics, we do not present an in-depth dynamical analysis using the large-scale field reconstructions.~~ , including regional instrumental series.

~~Standardising precipitation allows comparing different locations, periods or seasons on a common basis and thereby may attenuate the problems mentioned above. The core of the SPI calculation is the fit of a distribution function to the precipitation data. This allows evaluating and comparing percentiles of the data and their changes.~~ Our focus is not least to motivate the use of the Standardized Precipitation Index in hydroclimatic comparisons between different data sets in paleoclimatology. We use the SPI to study the consistency of the different sources of precipitation information for approximately the last 350 years. That is, we are looking how well the sources of information compare among each other. This is a limited aim, which is appropriate considering the various uncertainties especially in simulations, and reconstructions, but also in observations. We explicitly do not expect the simulation output to agree with the instrumental and paleo-observation data on the mean precipitation amount since spatial representations differ. We also do not expect them necessarily to agree on decadal variations in precipitation because of the presence of internal variability (compare, e.g., Deser et al., 2012b, a; Swart et al., 2015) potentially masking commonly forced external signals. Thus, even a large ensemble of simulations may not necessarily represent these variations (see, e.g., Annan and Hargreaves, 2011). Since we transform precipitation to the Standardized Precipitation Index over moving windows, our analyses essentially become comparisons between series of climatologies, thus potentially filtering shorter term internal variability.

~~These considerations motivate our assessment of the changes in percentiles and percentile changes of standardised regional precipitation data from small domains on~~ In the following, we first introduce and discuss our choices on data sets and methodology before comparing the ~~British Isles in observations,~~ data sets and discussing the results. A document asset supplements this manuscript but provides only analyses that are non-essential for our conclusions.

2 Data

Hydroclimatic changes affect humans and the environment most on the local and regional scale. Therefore, we focus on small domains and use precipitation data. Precipitation is a more tangible variable than, e.g., drought indicators like the Palmer Drought Severity Index (PDSI). We only use the single time series records instead of gridded products to avoid the possibly spurious non-climatic variance and other stastical artifacts potentially introduced by reconstruction techniques.

We aim at describing how much agreement we can find between different sources of information for precipitation in a small domain over a period with limited instrumental data, i.e., a period when we have to rely on reconstructions from paleo-observations. Such an assessment helps to increase our confidence in the estimates by the different sources of information. In turn, it also increases our understanding of past hydroclimatic variability.

Table 1. List of data sets by region, parameter, type of data, season used, and source for obtaining the data.

Location/Region	Parameter	Type	Season	Source
England-Wales	Precipitation	Observations	MAMJJ	https://www.metoffice.gov.uk/hadobs/hadukp/
South-West England	Precipitation	Observations	MAMJJ	https://www.metoffice.gov.uk/hadobs/hadukp/
South-East England	Precipitation	Observations	MAMJJ	https://www.metoffice.gov.uk/hadobs/hadukp/
Central England	Precipitation	Observations	MAMJJ	https://www.metoffice.gov.uk/hadobs/hadukp/
East-Anglia	Precipitation	Reconstruction	MAMJJ	https://www.ncdc.noaa.gov/paleo-search/study/12896
Southern-Central England	Precipitation	Reconstruction	MAMJJ	https://www.ncdc.noaa.gov/paleo-search/study/12907
Central England	Temperature	Observations	MAMJJ	https://www.metoffice.gov.uk/hadobs/hadcet/
Kew Gardens	Precipitation	Instrumental	MAMJJ	https://climexp.knmi.nl/
Pode Hole	Precipitation	Instrumental	MAMJJ	https://climexp.knmi.nl/
Oxford	Precipitation	Instrumental	MAMJJ	https://climexp.knmi.nl/
Europe	Precipitation	CCLM Regional climate model simulation	MAMJJ	http://doi.org/10.6084/m9.figshare.5952025
Europe	Temperature	CCLM Regional climate model simulation	MAMJJ	http://doi.org/10.6084/m9.figshare.5952025

We use observationally derived data sets, reconstructions, and simulation output in our main analyses. Additionally we use further observationally derived records and instrumental station observations. Table 1 lists the sources of information. For all analyses, we use primarily the spring-summer season from March to July (MAMJJ).

Data availability motivates the choice of the regional domain. For southern Great Britain, there exist observational regional domain composite records for temperature and precipitation, precipitation reconstructions, and ~~simulations. This standardisation procedure thus extends the available metrics for assessing the agreement in precipitation estimates between observations, reconstructions, and model simulations not only for periods without but also with comprehensive sets of climate and weather observations.~~ long instrumental records.

3 ~~Data~~

2.1 Observations

We choose the South of Great Britain as our domain of interest since there are precipitation observations available in form of the England-Wales precipitation data set (Alexander and Jones, 2000), its subdivisions, and instrumental records for Oxford (cf. Radcliffe), Pode Hole and Kew Gardens. Furthermore, there is also a long observational temperature record available for additional comparison, the Central England Temperature series (Parker et al., 1992). Croxton et al. (2006) find that the

England-Wales precipitation and the Central England Temperature well represent the climate of the South of Great Britain in the late 20th century.

Alexander and Jones (2000; see also Wigley et al., 1984) describe the England-Wales precipitation (EWP) data. It is available from the Met Office Hadley Centre in at monthly resolution extending back to the year 1766. Although there are a number of long instrumental records available from European stations (e.g. , via the climate explorer,) we The Met Office Hadley Centre also provides subdivisions of the data. We use those for South-West, South-East, and Central England. We concentrate on the England-Wales domain because there is also temperature data available in form of the long Central England Temperature series (Parker et al., 1992). Alexander and Jones (2000) Alexander and Jones (2000) describe the automated method of updating long precipitation series like the data by Wigley et al. (1984) while also ensuring the homogeneity of the data. Parker et al. (1992) similarly describe the production of temperature data to complement long-running series while maintaining quality-control and homogeneity.

A number of precipitation reconstructions exist for the European domain . We The Climate Explorer (http://climexp.knmi.nl/) provides access to a number of long series of monthly instrumental precipitation observations from the Global Historical Climatology Network (Peterson and Vose, 1997). We use those from Oxford, Kew Gardens, and Pode Hole in addition to the observationally derived Met Office Hadley Centre data sets. The Climate Explorer provides monthly data for these locations from 1697 to 1999, 1726 to 1994, and 1767 to 1999 CE, respectively. The later years in the Oxford record include missing values and we therefore only use data from 1767 to 1996 CE.

2.2 Reconstructions

To our knowledge, there are three precipitation reconstructions for small domains from the South of Great Britain, i.e., approximately within the domain of the England-Wales precipitation and the Central England temperature. These are for East Anglia (Cooper et al., 2013), for Southern-Central England (Wilson et al., 2013), and the reconstruction for Southern England by Rinne et al. (2013). The former two use tree-ring width data for their reconstructions, the latter uses tree-ring oxygen isotopes. There is additionally the work by Young et al. (2015), who scale a $\delta^{18}O$ composite record from Great Britain to the England-Wales precipitation.

We decide only to use the two tree-ring width based records. The main reason for excluding the Rinne et al. record is that it concatenates instrumental data from Radcliffe (cf. Oxford) station for 1894 to 2003 to the reconstructed values from 1613 until 1893. This reduces the time of overlap with the England-Wales precipitation data. The reconstruction by Rinne et al. (2013) is not publicly available, but the lead author provided us with the data. We provide a short assessment of the data in a supplementary manuscript asset.

Similarly, Young et al. (2015) scale their input $\delta^{18}O$ records by precipitation and provide the input series as supplement to their paper. Our supplementary manuscript asset provides a short assessment of a scaling using this data.

In the main manuscript, we only use the data by Cooper et al. (2013) and Wilson et al. (2013) for, respectively, East Anglia and Southern-Central England in March, April, May, June, July (MAMJJ). Cooper et al. (2013) and Wilson et al. (2013) identified this extended spring as the season their tree-ring width records are sensitive to for their reconstructions of precipitation. In the following, we compare the EWP England-Wales precipitation with the two reconstructions over the British Islesfor the South of Britain.

Wilson et al. (2013) and Cooper et al. (2013) already discuss the limitations of their respective reconstructions. Both reconstructions represent between 30% and 35% of regional interannual precipitation variance over the 20th century. Obviously, the reconstructions suffer from the limited lengths of the available tree ring samples. This has an effect on how much low frequency variability the reconstructions can resolve. The authors note variable relationships between tree growth and environmental controls for their regions in the past. Indeed there are periods when relations between trees and precipitation are not significant. Both studies are confident in the mid- to high-frequencies of their reconstructions but emphasize that their reconstructions have weaknesses in representing extreme years when compared to the observations. Cooper et al. (2013) explicitly call their paper "preliminiary" with respect to reconstructing low frequency precipitation variability.

Young et al. (2015) find that the two reconstructions from tree-ring widths strongly differ from their own scaled $\delta^{18}O$ data. The extended spring reconstructions are basically unrelated to the $\delta^{18}O$ data. Young et al. (2015), therefore, question whether both approaches reliably represent precipitation in the South of Great Britain. After discussing possible reasons for the disagreement, Young et al. (2015) conclude that the reconstructions by Cooper et al. (2013) and Wilson et al. (2013) are valid representations of oak growth in England, but they are not reliable representations of regional precipitation variations in contrast to the $\delta^{18}O$ data of Young et al. (2015).

2.3 Simulations

Our main comparison is to data We compare the observations and the reconstructions to output from a regional simulation with the model CCLM for the European domain over the period 1645 to 1999 as also used by Gómez-Navarro et al. (2014)and driven by a . Forcing for the regional simulation is from a global simulation with the MPI-ESM global climate model in its COSMOS set-up (see below). We use data output from 1652 onwards (Gómez-Navarro et al., 2014). Additionally we consider a number of global simulations from the PMIP3-ensemble (Schmidt et al., 2011) for reference. We choose the simulations with CCSM4 (Landrum et al., 2012), CSIRO-Mk3L-1-2 (Phipps et al., 2011), HadCM3 (Schurer et al., 2014), IPSL-CM5A-LR (Dufresne et al., 2013), MPI-ESM (Jungclaus et al., 2014), MRI-CGCM3 (Yukimoto et al., 2012) and the GISS-E2-R ensemble members 21, 24, 27 (Schmidt et al., 2014b). For details on the PMIP3 ensemble protocol, see Schmidt et al. (2011). Details of the regional simulation follow below.

The global simulations have different grid resolutions. We choose from each simulation the domain including grid points closest to the longitudinal and latitudinal borders 5.5W to 1.5E and 50.5 to 54.5N. This selection is somewhat arbitrary but we assume it sufficiently represents the EWP domain to allow meaningful comparison of changes in quantiles, although not in absolute quantile values. The different grids result in different means of seasonally accumulated precipitation in our subsequent analyses. While further model-biases may contribute, we assume the different grids to be the most prominent bias in the accumulated values. We choose the domain 5 to 0W and 50 to 55N as simulated counterparts of the Central England Temperature. (Gómez-Navarro et al., 2014).

The lateral forcing of the regional simulation is output from the Millennium-simulation COSMOS-setup of the Max-Planck-Institute Earth System Model (MPI-ESM). For details, see Jungclaus et al. (2010). This version of MPI-ESM couples the atmosphere model ECHAM5, the ocean model MPI-OM, a land-surface module including vegetation (JSBACH), a module for ocean biogeochemistry (HAMOCC), and an interactive carbon cycle. For the simulation, ECHAM5 ~~ran in~~ was run with a T31 ~~resolution~~ horizontal resolution and with 19 vertical levels. MPI-OM used a variable resolution between 22 and 250 km on a conformal grid for this simulation. The ensemble used diverse forcings. The driving simulation for the regional simulation with CCLM is one MPI-ESM simulation with all external forcings and a reconstruction of the solar activity based on Bard et al. (2000), i.e. with a comparatively large amplitude of solar variability.

The regional climate model CCLM simulation (Wagner, personal communication; see also Gómez-Navarro et al., 2014; Bierstedt et al., 2016) uses adjusted forcing fields relevant for paleoclimate simulations as also used with the global MPI-ESM simulation. These include orbital forcing and solar and volcanic activity. ~~The absence of a stratosphere in~~ Since the regional model ~~requires to include~~ does not represent the stratosphere, the regional simulation considers the effect of volcanic aerosols as a reduction in solar constant equivalent to the net solar shortwave radiation at the top of the troposphere in MPI-ESM. CO_2 variability is prescribed and changes in greenhouse gases CO_2, CH_4, and N_2O are based on data by Flückiger et al. (2002). Land-cover changes are included as external lower boundary forcing using the same data set as the MPI-ESM simulation (Pongratz et al., 2008). The presented CCLM simulation uses a rotated grid with a horizontal resolution of 0.44 by 0.44 degree and 32 vertical levels. The sponge zone of seven grid points at each domain border is removed and fields are interpolated onto a regular horizontal grid of 0.5 by 0.5 degree. ~~CO_2 variability is prescribed and changes in greenhouse gases CO_2, CH_4, and N_2O are based on data by Flückiger et al. (2002). Land-cover changes are included as external lower boundary forcing using the same data set as the MPI-ESM simulation (Pongratz et al., 2008).~~

We choose the domain including grid points closest to the longitudinal and latitudinal borders 5.5W to 1.5E and 50.5 to 54.5N to represent the England and Wales precipitation domain. This selection is somewhat arbitrary but we assume it sufficiently represents the England-Wales precipitation domain to allow meaningful comparison of changes in percentiles, although not in absolute percentile values. We choose the domain 5 to 0W and 50 to 55N as simulated counterpart of the Central England Temperature. The simulated East Anglia series represents the domain 0E to 2E and 52N to 53N, and we choose the domain 2.5W to 0E and 51N to 52.5N as equivalent for Southern-Central England. All analyses are for an extended spring season from March to July since this is the seasonal focus of the reconstructions. The appendix provides a short evaluation of the simulation against the observational CRU-data (Harris et al., 2014) over the European domain. We do not apply any bias correction to the simulation output.

So far, global simulations for the last millennium have notably coarser resolutions than the 0.44 by 0.44 degree of the regional simulation we use here (compare, e.g., Fernández-Donado et al., 2013; PAGES2k-PMIP3 Group, 2015). However, compared to other regional simulations this is only a coarse resolution dynamical downscaling. Thus, one may question the benefits of the approach compared to more recent higher-resolution global simulations, e.g., with the global models CCSM4 and CESM1 (Landrum et al., 2012; Lehner et al., 2015), which have resolutions of $0.9° \times 1.25°$.

A review by Ludwig et al. (2018, including two of the present authors) emphasizes that the demand for long simulation periods limits applications of regional models in paleoclimatology to relatively coarse 50km setups. Ludwig et al. (2018) conclude that regional simulations provide more realistic distributions for precipitation in the paleo-context. Flato et al. (2013, chapter 9 of the IPCC more ambiguous in their review but they emphasize the value of regional downscaling as a tool in addition to higher resolved global simulations.

3 Methods

Standardising precipitation data can avoid or at least attenuate some of the problems mentioned in the introduction. Transforming precipitation to standardised values allows to compare distributions easily One objective of this manuscript is to highlight how the concept of the Standardised Precipitation Index (SPI, McKee et al., 1993) adds additional perspectives on comparing various sources of information for periods with and without instrumental observations. Therefore, we shortly introduce the SPI-transformation procedure and how we use this information to subsequently compare precipitation estimates from observations, reconstructions, and a regional climate simulation.

3.1 The Standardized Precipitation Index – SPI

Standardising precipitation data facilitates comparing distributions between different locations, time-scales, periods, and data sources. For this purpose, McKee et al. (1993) introduced the Standardized Precipitation Index (SPI). Sienz et al. (2012) give a recent discussion of its biases Indeed the UK drought portal (https://eip.ceh.ac.uk/droughts) relies on the SPI, and there are recommendations to use the SPI in operational monitoring of meteorological drought (e.g. Hayes et al., 2011). Sienz et al. (2012) discuss biases of the methods.

Previous usage of the SPI in paleoclimatology generally focussed on the index series and did not consider further information available through the transformation from precipitation to SPI. For example, Domínguez-Castro et al. (2008) and Machado et al. (2011) cor SPI-series to differently derived hydroclimatic indices over approximately the last 500 years. Other studies reconstructed the SPI instead of absolute precipitation amounts (e.g. Seftigen et al., 2013; Yadav et al., 2015; Tejedor et al., 2016; Klippel et al., 2018). Lehner et al. (2012) use the SPI to compute pseudo-proxies from re-analysis data and long simulations with global climate models to test a reconstruction-method.

3.1.1 Transformation

The standardized precipitation index requires fitting a distribution function to the precipitation data. McKee et al. (1993) recommend at least 30 data points for successful distribution fits, but Guttman (1994) notes the lack of stability for small sample sizes and shows that higher order L-moments only converge for samples larger than about 60 data points. There are various candidate distributions as, e.g., Sienz et al. (2012, and their references) discuss . Sienz et al. (2012, and their references) discuss (see also Stagge et al., 2015).

In our analyses, we fit a Weibull distribution. Results differ only little if we fit Gamma or Generalised Gamma distributions (not shown). McKee et al. (1993) recommend at least 30 data points for successful distribution fits, but Guttman (1994) notes the lack of stability for small sample sizes and shows that higher order L-moments only converge for samples larger than about 60 data points.

We fit distributions over moving 51-year windows and a bootstrap procedure samples 1000 times 40 data points from each window to provide an estimate of sampling variability (~~compare~~ presented in Appendix Figure B1). Our procedure of the SPI-calculation follows the detailed description by Sienz et al. (2012).

3.1.2 Evaluation

Standardising precipitation data can avoid or at least attenuate some of the problems mentioned in the introduction. Transforming precipitation to standardised values provides further means to study the agreement or the lack thereof between different data sources.

By transforming to Standardized Precipitation Indices over moving windows, we essentially compare climatologies and potentially filter shorter term internal variability. One particular interest is to consider to which extent the different data sources describe comparable evolutions in various percentiles, e.g., representing extremes. If the transformation over moving windows filters a certain amount of internal variability, if boundary and forcing conditions are sufficiently equivalent in the simulation compared to the observed climate, and if simulated precipitation and the observed climate react equivalently to these conditions, precipitation distributions and their properties may change consistently between different sources of information. The results of Gómez-Navarro et al. (2015) give some indications that this expectation may be warranted. In the worst case, our analyses point out that one of the sources of information completely contradicts the other data sets.

For any given ~~sample data, the distribution fit gives among other things information about which precipitationamounts represent especially dry or wet conditions~~window, the fitted distribution parameters allow calculating various properties. For example, we can consider the changing amount of precipitation, which one would describe as average, extremely high, or extremely low for subsequent periods. In the SPI-literature, the 6.7th and 93.3th percentiles represent traditionally the regions of severe (and extreme) dryness/wetness of the probability density function. Accordingly, we subsequently ~~show~~ compare 6.7th and 93.3th percentiles for the fitted distributions ~~.~~ over time. Further, we can compare the moments of the distributions. We choose to show the square-root of the Weibull distribution variance, i.e., the Weibull standard deviation over sliding windows. The Appendix C shows parameters for the distribution fits.

~~Fitting distributionsover moving windows allows considering the changing amount of precipitation, which one would consider extremely high or low for subsequent periods, or~~ The fitted parameters allow further analyses, e.g., we can compare how likely a reference amount of precipitation is ~~in~~ for different periods. We ~~assess how the~~ do this for 50th, 6.7th, and 93.3~~percentiles for seasonal conditions change over the last 350 years in England based on tree-ring based reconstructions (Wilson et al., 2013; Cooper et al., 2013), long instrumental precipitation series (Alexander and Jones, 2000), and regional and global climate simulations (Gómez-Navarro et al., 2014; Schmidt et al., 2011)~~th percentiles in a reference year. We choose

1815 CE as reference year, since it is included in all data sets and it allows potentially equivalent analyses of the PMIP3 past1000 simulations (e.g., Schmidt et al., 2011).

The standardisation procedure provides further means to study the agreement or the lack thereof between different data sources. Agreement in Agreement on changes in percentiles and standard deviation increases our confidence in our understanding of forced and unforced changes in precipitation variability and projected future precipitation variations. Disagreement in on estimated changes may highlight differing internal climate variability between observed/reconstructed, reconstructed, and simulated data or it may signal that the simulated data simulation does not correctly capture forced variations.

We concentrate on the period 1700 to 1850 when best estimatesof external natural climate forcings show notable variations (compare Schmidt et al., 2011). All data sources tend to show shifts in the probability of precipitation amounts. However, changes are mostly small over this period and there is no general agreement on the direction of changes between all data-sources. Changes usually do not exceed bootstrapped confidence intervals over the full period (compare Figure B1)

3.2 Smoothing

Performing the transformation to standardised precipitation over 51-year windows results in smoothed estimates. For convenience, we additionally plot smoothed time series in a number of Figures. Filtered series are solely used for visualisation.

The gridded data sets used in this study have different spatial resolutions and therefore the statistics of simulated or of gridded precipitation may be different just due to this scale mismatch. Here, we average the data over the target regions England-Wales and Central England. Therefore, time series analyzed here are in theory representative of the same spatial domain and the originally different spatial resolutions should not influence the analysisWe use a Hamming window. In most cases, this has a length of 51 points but we also occasionally use different window lengths. The 51-point Hamming filter represents a different frequency cut-off than a simple 51-year moving median or moving mean as can be obtained from fitting the distributions over 51-year moving windows.

4 Results

4.1 Comparison of Temperature data

Figure 2provides a first impression of the regional southern British Isles climate in the form of the regional temperatures in the period of interest (1700 to 1850). It shows the 51-year Hamming low-pass filtered temperature recordsfrom observations and simulations. Vertical dotted lines represent the years 1700, 1784 (at the end of the volcanic eruption of Laki in 1783/1784), and 1816 (the year without a summer after the eruption of Tambora in 1815). The light grey line in the background shows an estimate of the Sunspot Numbers (Solanki et al., 2004) divided by 100 at 10-year intervals. Note that we calculate temperature anomalies in this plot over differing periods, i.e. over the full lengths of the respective data sets, because we are only interested in a tentative comparison. These periods are ~850 to 1850 CE for the global simulations, 1645 to 1999 for the CCLM data, and 1659 to 2014 for

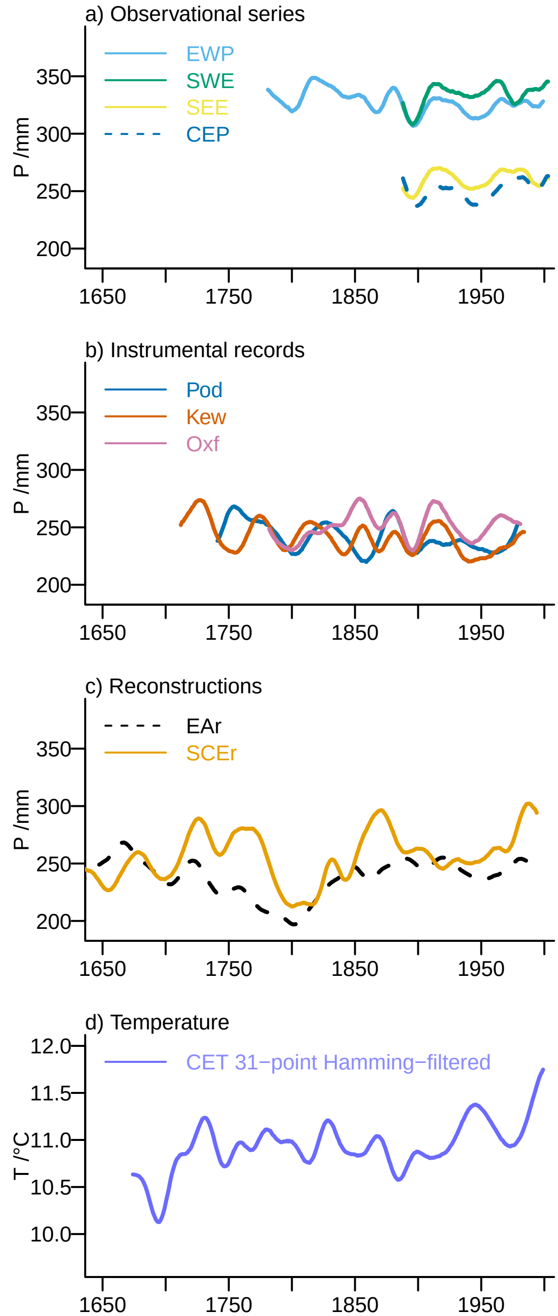


Figure 1. Visualisation of the observation based records for the extended spring season March to July (MAMJJ). We show 31-point Hamming-filtered time series for a) the Met Office Hadley Centre observational precipitation series for England-Wales (EWP), South-West (SWE), South-East (SEE), and Central England (CEP), b) the instrumental precipitation series for Pode Hole (Pod), Kew Gardens (Kew), and Oxford (Oxf), c) the precipitation reconstructions for East Anglia (EAr) and Southern-Central England (SCEr), and d) the Central England Temperature (CET) data.

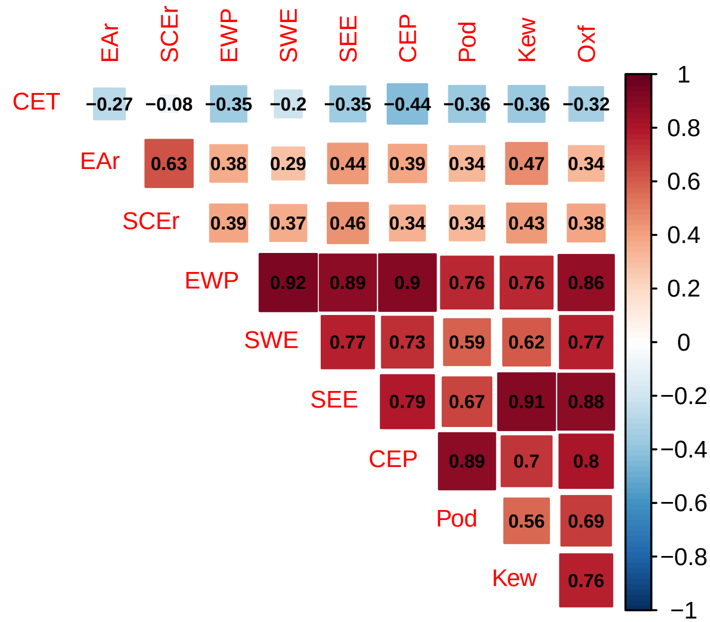


Figure 2. Correlation matrix for complete correlations between the observation or paleo-observation based data sets Central England Temperature (CET), East Anglia precipitation reconstruction (EAr), Southern-Central England precipitation reconstruction (SCEr), England-Wales precipitation (EWP), South-West England precipitation (SWE), South-East England precipitation (SEE), Central England precipitation (CEP), Pode Hole precipitation (Pod), Kew Gardens precipitation (Kew), and Oxford precipitation (Oxf). Complete correlations mean, we only use the years 1873 to 1994 for which all records have data. The season for all records is MAMJJ.

4.1 Relations among data sets

4.1.1 Observational data and reconstructions

Figure 1 provides a first impression of the observational and reconstruction data we use in the ~~CET data~~ following. All series are for the extended spring season from March to July on which we focus. Panels show 31-point Hamming-filtered time series. These allow a better qualitative assessment of the commonalities between the data sets and the differences compared to, e.g., 11-point or 51-point Hamming-filtered time series. Observational precipitation series from the Met Office Hadley Centre for South-West, South-East, Central England, and England-Wales show high agreement in their variations on these time-scales (see Figure 1a). The instrumental time series for Kew Gardens and Pode Hole show more disagreement in certain periods for the considered smoothing, i.e., they even evolve oppositely at certain times (see Figure 1b). The instrumental data for Oxford appears to agree better with the data for Kew Gardens, which is to be expected from the geographic locations of the stations. Visually, both reconstructions agree less well with the observational series and with each other than the observational data does (see Figure 1c). Figure 1d adds the Central England temperature data for MAMJJ for completeness sake.

Correlation matrices (Figure 2, and supplementary manuscript asset) and scatterplots (see manuscript asset) emphasize the differing agreement between the various data sources even more clearly on interannual time-scales. Figure 2 presents the correlation matrix for complete observations, i.e. for the period 1873 to 1994 when all records have data. Correlation coefficients change slightly if we consider pairwise complete records. Relations among precipitation data sets are always positive. They are very strong between the England-Wales data and its subdivions, between the Kew Gardens series and the South-East England data, between the Pode Hole series and the Central England data, and between the Oxford record and the South-East England data as well as the England-Wales precipitation. The relation between the two reconstructions is also rather strong over the sub-period. Correlations are, however, weaker between the reconstructions and the observed series.

There is a generally negative relation between the Central England temperature and the precipitation data sets. It is weakest for the Southern-Central England reconstruction but also rather weak for the East-Anglia reconstruction and the South-West England record from the Met Office Hadley Centre. Scatterplots emphasize that even the temperature-precipitation relations with larger correlations scatter widely (not shown). Temperature-relations are stronger for the observationally based data from the Met Office Hadley Centre and the instrumental series for the summer season June to August (not shown).

Correlations for non-overlapping 11-year averages are positive and strongest between the England-Wales precipitation and the two instrumental series (not shown, see supplementary manuscript asset, calculated for the period 1767 to 1986). This analysis gives also reasonable correlations ($r \approx 0.51$) between the pair of reconstructions and between the instrumental series. Otherwise, correlations for this resolution are weak. Correlations with the Central England temperature data are largest for the non-overlapping 11-year averages of the Kew Gardens instrumental series.

Simulations and observations lack an obvious common signal, not only at multidecadal timescales but also in the long-term centennial trend. For instance, the CET record shows a marked cool climate concurrent to the Late Maunder Minimum around year 1700. This feature is present in some simulations but not in all, although it is generally accepted that intense volcanic eruptions and the weaker solar activity of the Late Maunder Minimum resulted in such cool conditions. Somewhat more surprising is the lack of a clear long-term centennial trend in the simulations over the whole period of analysis. Obviously, the internal climate variability from atmospheric and oceanic processes is stronger at regional scales than at global scales and , thus, may dominate. This might reduce our hope in finding a common signal in precipitation.

4.1.2 (Paleo-)observational data and regional simulation output

The observed Central England Temperature (CET)is Figure 3 presents the two reconstructions and the only data whose England-Wales precipitation in comparison to the respective data from the regional simulation. All data are again for the extended spring season from March to July (MAMJJ), and the panels zoom in on the period of the regional simulation. We show the interannual time series and the 51-point Hamming filtered series shows some agreement to changes of the decadally averaged sunspot numbers. CET starts from a cold period prior to 1700 and then reaches a plateau of higher temperature that is intersected by short cold episodes around 1750 and early in the 19th century.

The regional simulation similarly has cold conditions about 1700 and then warms until the early second half of the 18th century with a subsequent transition to cold conditions in the Hamming-filtered representation.

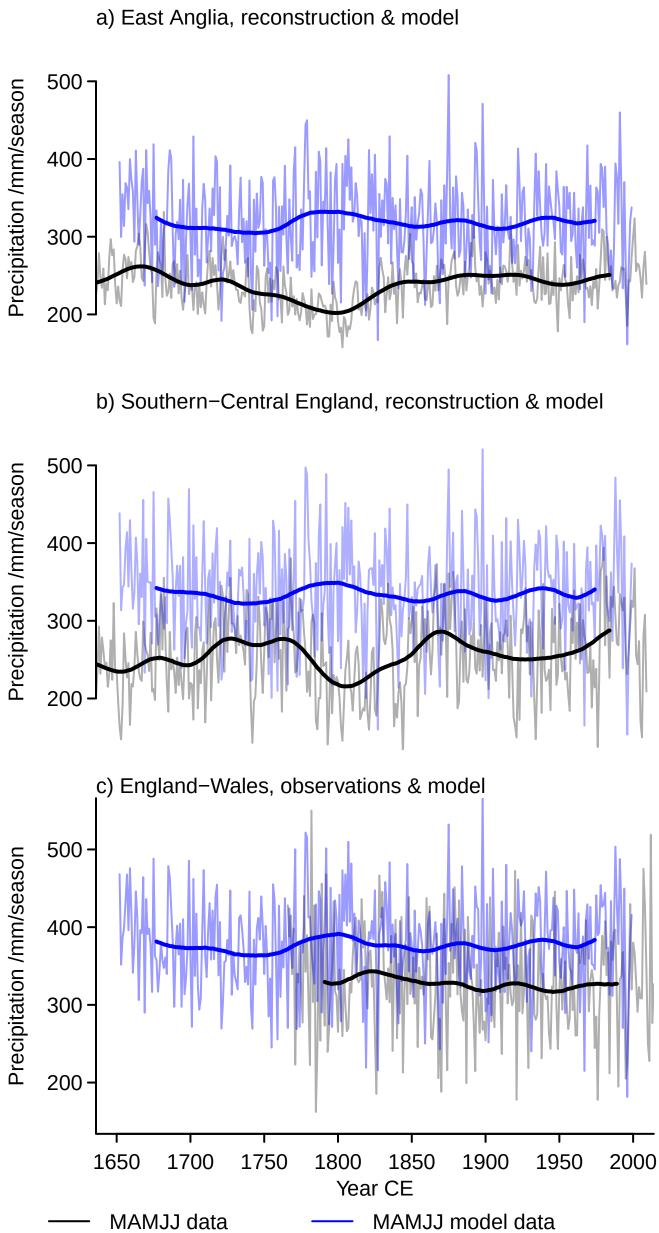


Figure 3. ~~Representations of Central England Temperature smoothed with a 51-point Hamming filter~~ Extended spring (~~colored~~MAMJJ) precipitation in ~~various datasets for the period 1650 to 1850 and the Solanki decadal Sunspot Number~~ (~~light grey in background, divided by 100~~paleo-)~~. Light colors are European domain large-scale mean temperatures.~~ observation based data and simulation output, a) ~~observational CET, b~~East Anglia precipitation in reconstruction (black) ~~CCLM~~ and regional ~~simulation, e~~model (blue)~~MRI~~, ~~d~~b) ~~MPI, e~~Southern-Central England precipitation in reconstructions (black) ~~IPSL, f~~and regional simulation (blue)~~HadCM3~~, ~~g~~and c) ~~GISS-E2-R-21, h~~England-Wales precipitation in observational data (black) ~~GISS-E2-R-24, i~~and regional simulation (blue)~~GISS-E2-R-27, j~~. We show interannual data (light colors) ~~CSIRO, k~~and 51-point Hamming-filtered data (solid colored)~~CCSM4~~.~~Vertical lines give the years 1700, 1784, and 1816.~~

Considering the evolution of the records, the 51-point Hamming-filtered time series show pronounced differences besides some common features for the reconstructions for Southern-Central England (Wilson et al., 2013) and East Anglia (Cooper et al., 2013) (bla lines in Figure 3a and b) similar to the representations in Figure 1. Both reconstructions feature a relative precipitation minimum centered on approximately the year 1800. The Southern-Central England reconstruction additionally displays a relative minimum in the early ~~19th~~ 20th century. ~~Noteworthy is a slight excursion with colder temperatures in the middle of the second half of the 18th century. Please note that the regional simulation includes volcanic variations only as reduction in an effective solar constant and uses a rather large solar forcing amplitude. Thus the late 18th century dip may be due to the Laki eruption on Iceland (D'Arrigo et al., 2011; Schmidt et al., 2012) whereas the strong warming may be due to the larger incoming solar radiation in the second half of the 18th century.~~

The observed England-Wales precipitation is available at monthly resolution from the year 1766 onward. The ~~PMIP3 simulations seem to show generally less~~ Hamming-filtered time series shows markedly less multi-decadal ~~variability but more centennial variability. Some simulations appear to react to~~ to centennial variability compared to the reconstructions, but the observations have much more interannual variability than the reconstruction for East Anglia and slightly more variability than the reconstruction for Southern-Central England (Figure 3c, black line). The filtered England-Wales time series also displays a slightly negative trend.

Differences between the simulated regional records are generally smaller (blue lines in Figure 3). Existing differences highlight the spatial heterogeneity of precipitation. A general feature for all regions is that excursions of the filtered simulation output often, but not always, are opposite to those of the reconstructions or observation time series.

There is an obvious bias in the absolute amounts between the simulation output and the other data sets. The simulation output series give larger precipitation amounts. We do not try to attribute this difference. We note that it is not as prominent for the more local comparison with the data from Rinne et al. (2013) for May to August and the ~~forcing history, others less so.The light colored estimates of a larger domain European temperature suggest a slightly larger forced response~~bias is generally slightly negative for the summer season June to August for England-Wales precipitation (not shown, see supplementary manuscript asset). We assume that the differing spatial representations sufficiently explain the mismatch. However, the change of sign in the bias for the summer season suggests that the simulation overestimates spring precipitation, underestimates summer precipitation, and the positive spring bias is larger than the negative summer bias. See also Appendix A for a comparison of the simulation to observational data over the full European model domain.

This initial comparison already shows varying levels of agreement for the chosen data sets derived from observations and the reconstructions. It highlights that the relation between the reconstructions and the observational data sets are weaker than between the instrumental data and the observational indices on interannual time-scales. Note that the regional observational indices include information from the instrumental data. On longer time-scales the reconstructions align less well among each other than the observationally derived time series. However though possibly not surprisingly, the local, purely instrumental series also show more disagreement among each other than the derived larger domain products. Filtered regional time series evolve often visually oppositely in the simulation compared to the reconstructions and the observations.

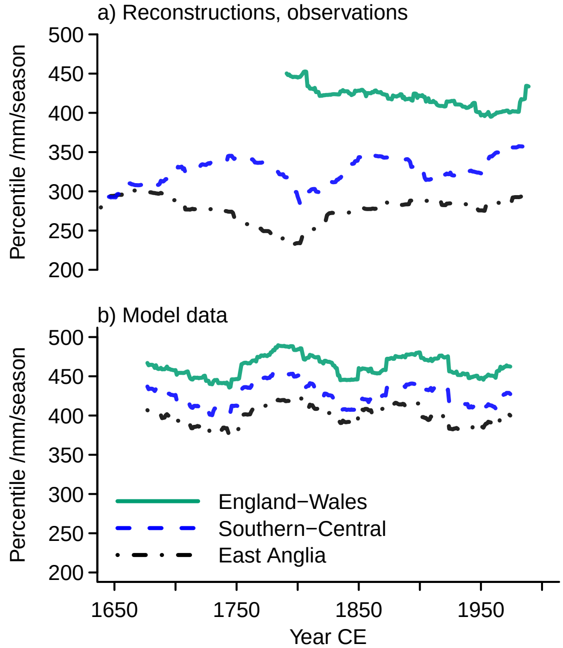


Figure 4. Visualisation of the MAMJJ precipitation amount identified as severely wet (93.3th percentile) over 51-year windows for England-Wales (green solid lines), Southern-Central England (blue dashed lines), and East Anglia (black dash-dotted lines) in a) reconstructions and observations, and b) simulations.

4.2 ~~Standardised Precipitation~~

So far, we used the precipitation and temperature data. In the following, we mainly use the information obtained via the transformation to standardised precipitation indices.

~~The lacking agreement between the temperature data in Figure 2 reduces our hope of finding agreement in the precipitation data~~

4.2 Comparing standardised precipitation data

Figure 4 to 6 add, respectively, the comparisons of the wet, i.e. 93.3th, percentile, the dry, i.e. 6.7th, percentile, and the square root of the Weibull distribution variance to the comparison of the interannual and filtered time series in the previous section.

4.2.1 Observations vs. Reconstructions

Since they represent different regions, we do not expect agreement in the absolute precipitation amounts representing wet conditions between the England-Wales precipitation data and the reconstructions in Figure 4a. We note that the difference between the wet percentile for the England-Wales precipitation and the reconstructions is larger than for the average amounts, indicating a wider distribution for the data based on instrumental observations. Precipitation histograms confirm this (not

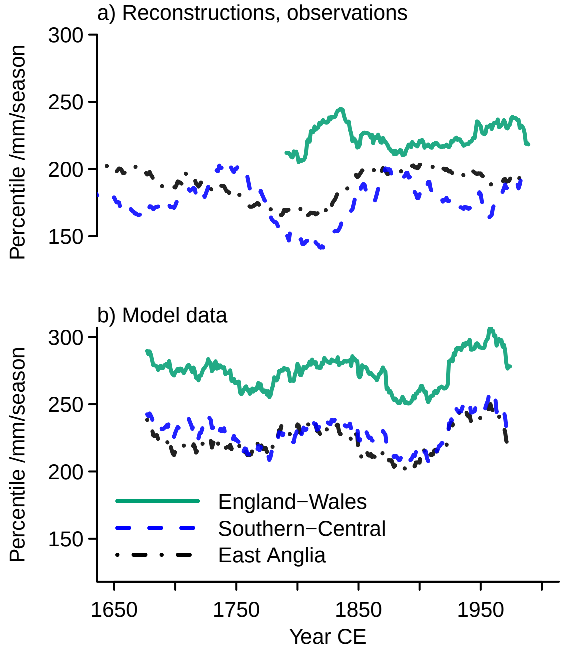


Figure 5. Visualisation of the MAMJJ precipitation amount identified as severely dry (6.7th percentile) over 51-year windows for England-Wales (green solid lines), Southern-Central England (blue dashed lines), and East Anglia (black dash-dotted lines) in a) reconstructions and observations, and b) simulations.

shown). On the other hand, differences are smaller for the dry percentile (Figure 5). Nevertheless, this is a sign that the reconstructions underestimate the width of the precipitation distributions of 51-year window climatologies.

Reconstructed and observation-based time series show a slightly opposite trend for the wet percentile over much of the period of the observational England-Wales time series (Figure ?? compares observations, reconstructions, and simulations for different regions of the United Kingdom. The reconstructions for Southern-Central England (Wilson et al., 2013) and East Anglia (Cooper et al., 2013) show some common features for the 51-point Hamming filtered representations (black lines in Figure ??a)but also pronounced differences. The panel zooms in on the period of the regional simulation. Both reconstructions feature a relative precipitation minimum centered on about 1800 but the Southern-Central England data enters it later.On the other hand, 4). Smaller scale variations in the relative minimum in the early beginning of the wet percentile series are also opposite. The dry percentile series lack the clear overall trend but multidecadal variations evolve oppositely between reconstructed and observed dry percentiles (Figure 5).

The opposite trends in the wet percentiles mean that the observed 93.3th, i.e. wet, percentile represents lower precipitation amounts in the middle of the 20th century compared to the late 18th century, while the reconstructed wet percentile represents larger precipitation amounts in the middle of the 20th century is more prominent in this data set.The percentilesfor compared to the late 18th century (Figure 4). Similarly the opposite multidecadal variability in the 6.7th, i.e. dry, percentiles of reconstructions and observations means that when the reconstructions represent a drying of the dry percentiles, the observations indicate that

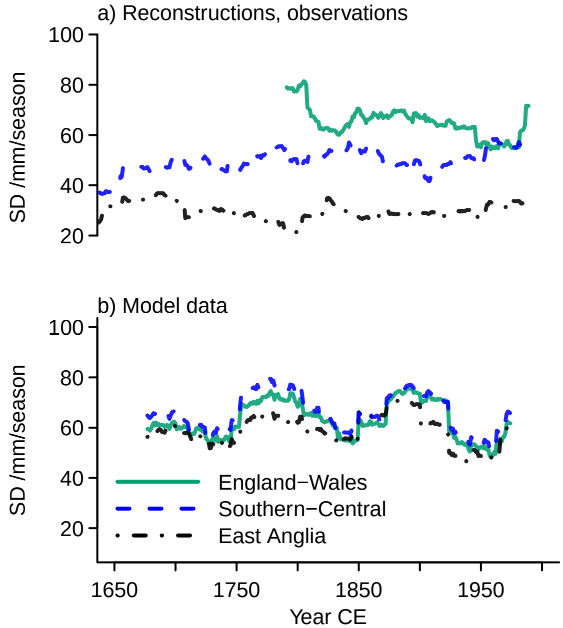


Figure 6. Visualisation of Weibull standard deviations over 51-year windows for MAMJJ precipitation for England-Wales (green solid lines), Southern-Central England (blue dashed lines), and East Anglia (black dash-dotted lines) in a) reconstructions and observations, and b) simulations.

very dry conditions are already identifiable for larger precipitation amounts in a period and vice versa (Figure 5). Generally, the series for the severe to extreme dryness (Figure ??g) and wetness (Figure ??d) and wetness percentiles reflect the smoothed evolution . We opt to show the Hamming filtered data instead of the 50th percentile of the fitted distribution. We are aware that the 51-point Hamming filter represents a different frequency cut-off than a simple 51-year moving medianof the respective data set.

We note that the data of Rinne et al. (2013) for Southern England in summer display an apparent opposite evolution of wet percentiles for the period of overlap between reconstruction and observations. On the other hand dry percentiles agree well (not shown, see supplementary manuscript asset).

Parameters for the fitted distributions also allow to evaluate the moments of the distributions. Estimates for the Weibull standard deviations (SD, Figure 6) differ between observations and reconstructions as expected from the previously noted differences in percentiles. The reconstructions do not show a clear evolution in the Weibull standard deviations. The observations show a slight reduction in the standard deviation until the middle of the 20th century, with a strong increase afterwards.

a) East Anglia and Southern-Central England precipitation in reconstructions and regional simulation, annual and 51-point Hamming filtered, b) England-Wales precipitation in observation and regional simulation in MAMJJ and JJA, annual and 51-point Hamming filtered, c) 51-point Hamming filtered England-Wales precipitation in the PMIP3 simulations. d,e,f) 6.7 percentiles over 51-year windows for the data in a,b,c); g,h,i) 93.3 percentiles over 51-year windows for the data in a,b,c), j,k,l)

Weibull Standard deviations over 51-year windows for the data in a,b,c). Note the different ranges of the x-axes between the PMIP3-simulations and the other columns. Left two columns are for the period 1650 to 2000; right column is for the period 1650 to 1850 for the PMIP3-simulations.

4.2.2 Simulation output

Differences are generally smaller between both regionsfor their approximate representations in the regional simulation data (blue lines in Figure ??, left column). The existing differences, however, highlight the spatial heterogeneity of precipitation. Differences between both simulated data sets become more notable in the percentiles, which The simulated time series in Figure 3 show large similarities between regions. This is also the case for the wet and dry percentiles as well as for the standard deviations. Indeed, the respective statistics evolve simultaneously among the different regions, and the standard deviations overlap (Figures 4 to 6).

Thus, differences between regional domains are smaller for their simulated representations compared to the observed or reconstructed records. They are slightly more notable for the moving window statistics compared to the Hamming-filtered series. Dry percentiles are very similar for East Anglia and for Southern-Central England in the simulation but wet conditions require larger precipitation amounts for Southern-Central compared to East Anglia. Appendix B highlights that this may be due to sampling variability(compare Appendix B). Smoothed . Smoothed simulated data and wetness percentiles evolve similarly, but opposite evolutions of the dryness and wetness percentiles results result in widening and shrinking of the distributions after about approximately the year 1800. The regional simulation data shows a maximum instead of the reconstructed minimum in precipitation measures centered around 1800. There appears to be agreement in the late 19th century between the simulation and

4.2.3 Simulation output vs. observationally derived data and reconstructions

Simulations and reconstructions agree only minimally (Figures 4 to 6). The simulation appears to agree sligthly with the reconstruction for Southern-Central England in their smoothed evolutions and in the wetness percentile . On the other hand, the dryness percentiles the late 19th century in the wet percentile (Figure 4). However, then the dryness percentile evolve in an opposite way (Figure 5).

If we define a period of interest as between 1650 This apparent opposite evolution is the most common feature when comparing the percentiles derived from the simulation and 1850, we can generally conclude that the regional simulation and from the reconstructions. When the percentile series for the reconstructions show minima, the selected reconstructionsfor the southern British Isles evolve oppositely. We note that different percentiles are approximately in phase and in the same direction in the reconstructions , whereas the inter-percentile ranges may widen or contract in the simulated datasimulation commonly shows maxima and vice versa. Obviously, using an ensemble of regional simulations probably would show different trajectories. This does not preclude per-se that the model is capturing basic physical characteristics of precipitation variability in northwestern Europe.

Next, we compare these reconstructions and simulations with the The smoothed representations of the simulation output and the smoothed observed England-Wales Precipitation in the months MAMJJ that is available in monthly resolution from the year 1766 onward (Figure ??, central columnprecipitation show only small multidecadal variations, which appear to be more or less opposite in simulated and observed estimates (compare above Figure 3). The England-Wales precipitation data for MAMJJ shows slight negative trends in the smoothed mean data and in the wet percentile, but a slight positive tendency in the dry percentile indicating a narrowing of the distribution. The reconstruction appears to show more multi-decadal variability compared to the low-pass filtered observations. The weak upward and downward excursions of the smoothed observed data are opposite to those of the simulation data. One may infer some commonalities for the quantiles.

The right column of Figure ?? shows for comparison the representation of wet percentiles do not show any agreement although they both have a relative maximum in the late 18th century (Figure 4). On the other hand, the dry percentiles show approximate agreement in their evolutions with maxima in the early 19th century and in the middle of the 20th century (Figure 5). Similarly the Weibull standard deviations show some commonalities between the simulated representation of the England-Wales precipitation in a selection of PMIP3 past1000 simulations for the period 1650 to 1850. Please note that the precipitation scales as well as the x-axes differ from the other columns. These panels solely illustrate the diversity of the PMIP3 ensemble including notable opposite anomalies between models in the smoothed data series and not just unstructured evolutions. That is, e.g., the late and the observations (Figure 6).

We note that there is neither any clear commonality nor any overly opposite evolution in the dry percentiles when comparing the regional simulation to the reconstruction for Southern England summer precipitation by Rinne et al. (2013, not shown, see supplementar The wet percentiles, however, evolve oppositely in the 18th century is either relatively dry or relatively wet but generally not just in transition. None of the smoothed PMIP3 series agrees well with the regional simulation. but then show a common positive trend in the 19th century (not shown, see manuscript asset).

Parameters for the fitted distributions allow evaluating the moments of the distributions. The bottom row of Figure ?? shows the Weibull standard deviation in gliding time windows. The various data sets again lack any clear commonalities. Only the England-Wales Precipitation for MAMJJ and its counterpart in the regional simulation may be described as being partially similar but the data already differ again if we consider the boreal summer season, JJA.

The moving window transformations provide the data to show the

4.3 Changes in probability of certain precipitation amounts

In the methods section, we describe the procedure of calculating standardized precipitation indices over moving time windows. We obtain a distribution fit for each time window. The parameters of the fit for a window allow us to identify the probability of a precipitation amount for the respective window. Figures 7 to 9 present changes in the probability of certain amounts of precipitation, i.e. lines are the changing percentiles represented by a certain given amount of precipitation over time(Figure 1). We analyse changes in the . The Figures show these changes for the precipitation amounts representing 93.3th, 50th, and 6.7th percentiles. The reference for this , respectively, in a reference window. For this comparison, the reference is the distribution of precipitation in the window centered around the year 1815CE1815 CE. We estimate and plot the percentiles that correspond to

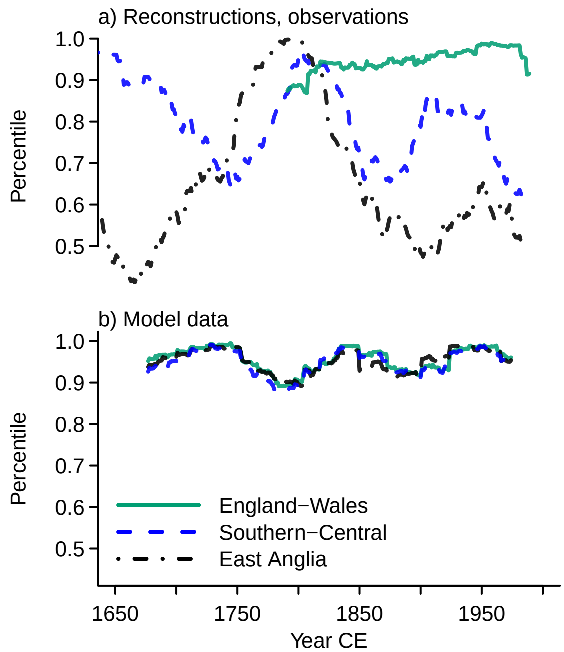


Figure 7. Visualisation of which percentiles the 93.3th percentile MAMJJ precipitation amount for the reference window centered in year 1815 CE represents over time for England-Wales (green solid lines), Southern-Central England (blue dashed lines), and East Anglia (black dash-dotted lines) in a) reconstructions and observations, and b) simulations.

these reference precipitation amounts in other time windows. ~~We choose 1815 as base year, since it is included in all data sets and it is not yet the last year of the PMIP3 past1000 simulations.~~

~~There is a slight increasing trend over time in the observed~~ The England-Wales ~~MAMJJ precipitation quantiles corresponding to~~ precipitation shows a slight increase over time in the ~~50th and~~ reference 93.3~~th percentiles in the~~ th percentile in the year ~~1815. The quantile corresponding to~~ 1815 CE (Figure 7a). Recently, there is a steep decrease in the series. Similarly, the 50th percentile for 1815 CE represents slightly larger percentiles over time (Figure 8a). On the other hand, there are weak multi-decadal variations in the series for the 6.7th percentile in the observations, and the 6.7th percentile from 1815 ~~appears to become~~ CE may become slightly less likely over time (Figure ~~1, middle column~~9a).

~~The regional simulation does not show a comparable trend but displays similar overlaid variationsthough with stronger amplitude. The PMIP3 ensemble again shows diverse behavior. Most series display some kind of trend of previously increasing or decreasing probability of the percentiles for the year 1815.~~ Before turning to the reconstructions, we shortly note that the simulations show similar trajectories for all three percentile values and all three regions. There are not any obvious trends, but the series show multidecadal variations. The window centered in the year 1815 CE falls within a minimum or at the end of a minimum. The respective precipitation amount generally represents larger percentiles before the time window centered in 1815 CE. After this time window, the 6.7th and 93.3th percentiles both approach a maximum in the series (Figures 7b and 9b). However, the 93.3th percentiles reach it about the year 1850 CE and the 6.7th percentile only in approximately the year

Changes in the cumulative probability over 51-year windows represented by a,b,c) the 93.3 percentile, d,e,f) the 50 percentile and f,g,h) the 6.7 percentiles for the reference year 1815 for a,d,g) East Anglia and Southern-Central England precipitation in reconstructions and regional simulation, b,e,g) England-Wales precipitation in observation and regional simulation in MAMJJ and JJA, c,f,i) England-Wales precipitation in the PMIP3 simulations. Note the different ranges of the x-axes between the PMIP3-simulations and the other columns. Left two columns are for the period 1650 to 2000; right column is for the period 1650 to 1850 for the PMIP3-simulations.

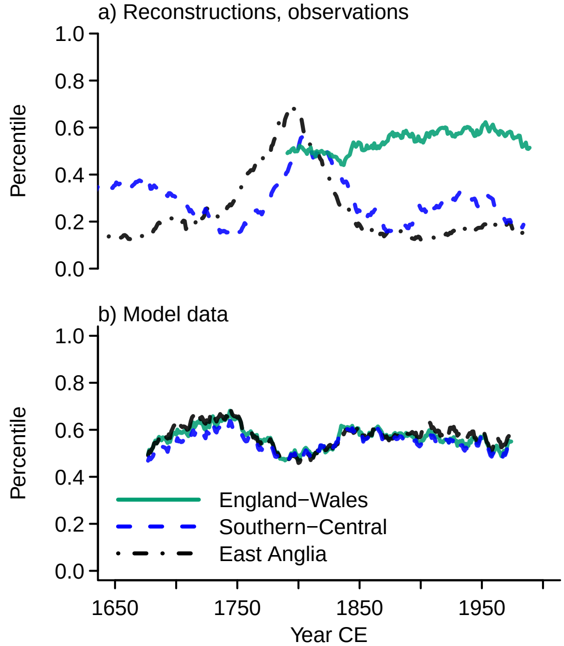


Figure 8. Visualisation of which percentiles the 50th percentile MAMJJ precipitation amount for the reference window centered in year 1815 CE represents over time for England-Wales (green solid lines), Southern-Central England (blue dashed lines), and East Anglia (black dash-dotted lines) in a) reconstructions and observations, and b) simulations.

1900 CE, when the 93.3th percentile is again in a relative minimum. Thus, the wet and dry percentiles evolve oppositely from the early 19th century onwards, i.e. the distribution widens and shrinks since approximately the year 1850 CE. The median reference for 1815 CE also represents larger percentiles later but there is a slight decreasing trend from approximately the mid-19th century to the end of the simulation (Figure 8b).

The reconstructions for East Anglia and South West Southern-Central England have some peculiar features (Figures 7a to 9a). For one, it is not ideal to choose a reference year from the period around 1800. 1800 CE. The 6.7th percentile in 1815 CE is much less likely previously and later earlier and later in both regions (Figure 9a). Similarly, average precipitation around 1815 CE represents approximately the 20th percentiles in earlier and later periods for East Anglia (Figure 8a) but also represents much smaller percentiles in later periods for Southern-Central England. Severe and extreme wet conditions from this period may even represent long-term average conditions for East Anglia (Figure 7a). We note that comparisons to the data by Rinne et al. (2013) do not feature such peculiarities (not shown) but using a simple scaling approach for the $\delta^{18}O$ data of

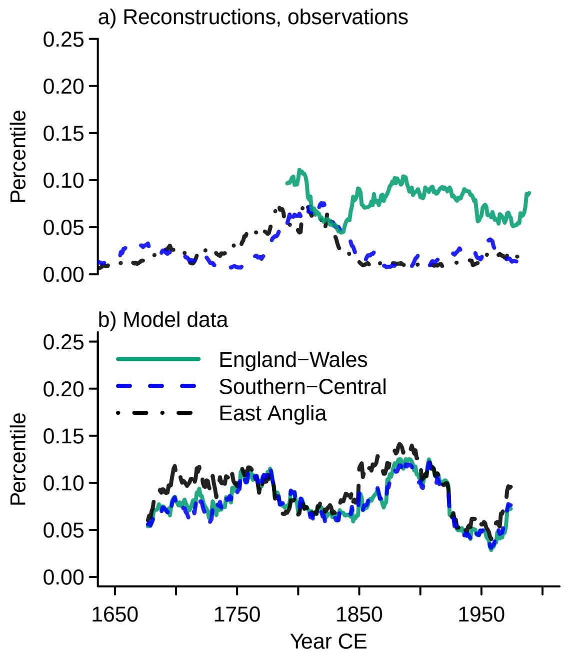


Figure 9. Visualisation of which percentiles the 6.7th percentile MAMJJ precipitation amount for the reference window centered in year 1815 CE represents over time for England-Wales (green solid lines), Southern-Central England (blue dashed lines), and East Anglia (black dash-dotted lines) in a) reconstructions and observations, and b) simulations.

Young et al. (2015) gives similar results prior to approximately the year 1850 CE (not shown, but compare information given in the supplementary manuscript asset).

Thus, the distributions for reconstructed precipitation show larger shifts to more precipitation amounts compared to the simulations and observations during this period. A possible interpretation may be that the reconstructions are less likely to capture interannual variability and are more likely to represent the decadal frequency band. The regional simulation and the reconstructions show again an approximately opposite evolution for East Anglia and South West England.

4.4 Relation between Temperature and Precipitation

We pointed above at how the temporal evolutions of regional temperature differed In general, there are not any clear common evolutions between the different data sets and then presented the differences in precipitation variations between the simulations, the reconstructions, before the 20th century. Only the dry percentiles in the simulation and the observations . Assuming that there is a clear relationship between regional temperature and regional precipitation, we next detail whether the different data sources may agree on this relation.

Correlations between Central England temperature and precipitation distribution measures over 101-year windows, a,b,c,d) Reconstructions, observational data, and regional simulation, e,f,g,h) the PMIP3 ensemble England-Wales precipitation; a,e)

6.7 percentile, b,f) 50 percentile, c,g) 93.3 percentile, d,h) Weibull standard deviation. Note the different ranges of the x-axes between the PMIP3-simulations and the other column. The left column is for the period 1650 to 2000; the right column is for the period 1650 to 1850 for the PMIP3-simulations.

Figure 3 shows gliding correlations over 101-year windows between 51 year running means of the Central England Temperature and the 51-year distributional properties. The figure shows, from top to bottom, correlations with dry percentile, 50 percentile, wet percentile, and Weibull standard deviation. We only use the windows centered between 1625 to 1825 for the PMIP3 simulations, 1677 to 1877 for CCLM and the full period where Central England Temperature and England-Wales Precipitation are available (1766 to 2014). Obviously, 101-year correlations of 51-year running measures are only of illustrative value. These series have of the order of one effective degree of freedom.

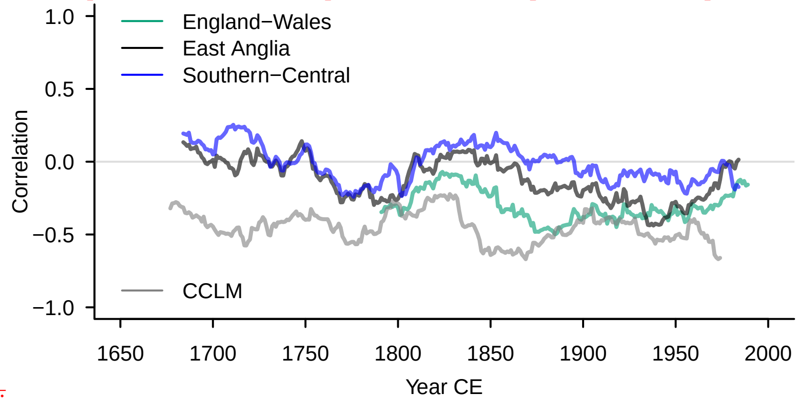
Considering the PMIP3 past1000 ensemble there is not any common relation between regional temperature and regional precipitation (Figure 3e-h). We emphasize the MPI-ESM and GISS24 simulations in Figure 3. First, they evolve oppositely in the relation of the dry percentile with temperature. Secondly, there is a continuous positive relation of the median to temperature in GISS24 but the relation changes from positive to negative correlation in MPI-ESM. may evolve similarly (Figure 9). Interestingly, there is an apparent contrast between simulation and reconstructions with potentially opposite evolutions prior to the 20th century in all shown series. In the 20th century, on the other hand, some commonalities may be inferred at least for the series representing the reference 93.3th percentile (Figure 7).

The relation between Central England Temperature and England-Wales Precipitation shows an increasingly positive relation for the dry percentile but an increasingly negative relation for other distributional measures of the observational data setsMost prominent in these analyses is that the distributions for reconstructed precipitation show large shifts to larger precipitation amounts compared to the simulations and observations. In contrast, the simulation and observations vary only within a rather narrow range. This may relate to the weaknesses of the reconstructions in representing not only low-frequencies but also extremes (compare Cooper et al., 2013; Wilson et al., 2013). The regional simulation 's severe percentiles and its variability have relations to temperature, which are broadly comparable to the observations but the median remains positively related to temperature, albeit with an intermediate phase of no clear relation.

Both reconstructions show important shortcomings. Whereas the median observations only recently become highly related to temperature, the reconstructions show such a relation for much of the CET period. For and the reconstructions show again an apparent opposite evolution for East Anglia and Southern-Central England, the positive relation fails in the most recent part of the records. All sources of information tend to show shifts in the probability of precipitation amounts.

The relation between temperature and dry percentiles is negative in the reconstructions and positive in the observations. Similarly observations suggest a strongly negative relation between wet percentiles and temperature for windows centered in the early 20th century but this feature is only weak in the reconstructions. In turn, the relation between the Weibull standard deviation and the temperature becomes strongly negative in observations in recent time-windows but it is weakly positive in the reconstructions.

Interannual correlations over gliding 51-year windows between Central England temperature and precipitation data sets, a) Reconstructions, observational data, and regional simulation, b) the PMIP3 ensemble England-Wales precipitation. Note the different ranges of the x-axes between the PMIP3-simulations and the other panel. Panel a) is for the period 1650 to 2000, panel b) is for the period 1650 to 1850 for the



PMIP3-simulations.

Figure 10. Interannual correlations over 51-year windows between extended spring (MAMJJ) Central England Temperature and various precipitation records: extended spring (MAMJJ) precipitation series for observational England-Wales-precipitation (green), reconstructed East Anglia precipitation (black), reconstructed Southern-Central England precipitation (blue). The grey line is for the simulated representations of the England-Wales MAMJJ precipitation and the Central England Temperature in MAMJJ.

We note that the authors of the reconstructions already point to potential issues with the sensitivity of the proxy-records (Cooper et al., 2013; Wilson et al., 2013). A possible reason is that the proxies, theoretically representing a precipitation signal, also contain a temperaturesignal, for instance, if they are sensitive to soil moisture.

4.4 Relation between Temperature and Precipitation

The high amount of internal variability on local and regional scales complicates the comparison among different data sources when studying small regions. We only shortly explore the interrelation between the regional temperature and the precipitation variability. We show how interannual correlations between the precipitation records and temperature series evolve over time. Figure 10 plots sliding interannual correlations for 51-year windows between the observed and reconstructed precipitation data and the Central England temperature as well as the correlation between simulated England-Wales precipitation and simulated Central England temperature. We plot correlations for the untransformed precipitation records. All records are for the MAMJJ-season.

Since correlations between the running measures over moving windows capture only the very low frequent variability in these moving windows, Figure 4 adds interannual correlations over 51-year windows. We expect variability of moving correlation coefficients simply due to sampling variability (Gershunov et al., 2001). For example, a bootstrap procedure following Gershunov et al. (2001) suggests a 90% credible interval for 51-year moving window correlations of between about approximately -0.59 and about approximately -0.21 for a correlation of about approximately -0.43 between simulated CET and EWP Central England Temperature and England-Wales precipitation over the full period. That is, variations in Figure

~~4~~ 10 are probably within the sampling variability estimates for 51-year moving window correlations. That further implies ~~,~~ that for overall uncorrelated data we can expect some windows to show statistically significant correlations. We do not show significance levels in Figure ~~4~~10. We note that for 51-year windows and the ~~time-series~~ time series characteristics of the data (e.g., approximately uncorrelated noise for seasonal precipitation), one may regard absolute values of correlation coefficients larger than 0.23 as ~~significant~~statistically significant at the 5% level.

On interannual timescales and over 51-year moving windows, all data sets evolve similarly in Figure ~~4a~~10. However, ~~recently the regional simulation behaves opposite to the reconstructions and the observations~~observed and reconstructed data show weaker correlations in the late 20th century, while the correlation strength increases in the regional simulation. Both reconstructions do not show any statistically significant relation between temperature and precipitation over the full period. The reconstruction for East Anglia is intermittently negatively correlated with the temperature data. The observations show a notable negative relation from the second half of the 19th to the mid-20th century. Only correlations between the regional simulation temperature and precipitation are ~~constantly negative . While the relation weakens recently in the observations, the relation strengthens slightly in the simulation. The PMIP3 simulations are more likely to show a positive relation between temperature and precipitation in the region of interest over 51-year moving windows. However, the ensemble does not agree on a relationship~~negative and relatively strong ($r \approx 0.5$) throughout the full period.

The observed negative relation ~~between temperature and precipitation points to the strong influence of the large-scale atmospheric circulation on the regional climate of the British Isles. Then, advection of colder and moist air masses from the Atlantic by low-pressure systems dominates the precipitation-temperature relation. Indeed composite maps for temperature and precipitation for years of anomalous North Atlantic Jet positions (Trouet et al., 2018) support this large influence of the westerlies on the relation between temperature and precipitation on the British Isles. More importantly~~ is well known. For example, Crhová and Holtanová (2018) show a slightly negative correlation between temperature and precipitation in observations over the southern British Isles in spring and summer~~, and~~. They also show that regional climate simulations usually capture this feature successfully.

~~Figures 3 and 4 highlight that moving correlations evolve differently for interannual and smoothed data . This also holds for different smoothing intervals (not shown). Relations between temperature and precipitation are time-scale dependent~~

5 Discussions

Our understanding of hydroclimatic changes for future and past climates increased notably in recent years (compare, e.g., PAGES Hydro2k especially for drought (see Cook et al., 2018). Nevertheless comparing our various sources of information for past hydroclimatic changes remains challenging (compare PAGES Hydro2k Consortium, 2017).

Hydroclimate comparisons between different data sources may focus on floods, on drought using indices like the PDSI, or on precipitation, including the SPI used in this study. Humans notice effects of climatic changes mostly on local to regional scales. We expect that changes in precipitation are of larger immediate relevance for local communities than changes in drought indices. Thus, we study precipitation changes in regional small domains.

In this section, we more extensively discuss the SPI, our data choices, and our results. We also discuss additional data sets presented in the supplementary manuscript asset.

5.1 Method

Much research on hydroclimatic variability focusses on drought because of its effects on society and environment. Based on criteria suggested by Keyantash et al. (2002), the Interregional Workshop on Indices and Early Warning Systems for Drought proposed the Standardized Precipitation Index (SPI, McKee et al., 1993) as common index to monitor meteorological drought (Hayes et al., 2011). The SPI should complement previously used indices and facilitate comparability between different regions. Raible et al. (2017) find the SPI to be a reliable drought index for Western Europe including the British Isles. The standardisation allows further applications, e.g., flood monitoring (Seiler et al., 2002), and the easy comparison of normal, dry, and wet conditions between different sources of data.

~~Furthermore the agreement~~ The SPI uses only precipitation, which makes it an ideal and relatively straightforward tool for comparing hydroclimatic data between different data sources~~about the relation between temperature and precipitation is apparently~~ . Precipitation is a standard output of simulations, long instrumental records exist for various locations, and a number of reconstructions exist as well although paleo-observations may represent soil moisture rather than precipitation.

However, as the SPI uses only precipitation, it is of less value when the interest is in, e.g., the water supply, runoff, or streamflow (but see Seiler et al., 2002). The focus on precipitation also limits the applicability for studying temperature sensitive parts of the hydrological cycle and impacts on biological and anthropogenic systems (e.g., PAGES Hydro2k Consortium, 2017; Ke

Most importantly, the interpretation of our results relies on the robustness of the SPI-transformations. Sienz et al. (2012) highlighted that the Weibull distribution performed better in transforming the England-Wales precipitation data on a monthly time-scale ~~dependent for the short data series we use, according to Figures 3 and 4. For decadal data , observations, a reconstruction~~compared to a number of other distributions. However, other distributions outperformed the Weibull distribution for other data sets and other SPI time-scales.

We fit distributions over sliding 51-year windows. While we thus use more data points than recommended by McKee et al. (1993), we still use less than the 60 points for which Guttman (1994) finds convergence of higher order L-moments. Appendix Figure B1 shows 95% intervals of a bootstrap procedure sampling 1000 times 40 data points from each window and fitting distributions to these samples. Uncertainty on the fitted distributions varies in size over time and between data sets. Indeed, there are periods when sampling variability is so large that apparent differences in distributional properties between periods are not significant for most sources of information.

In a sense, the SPI calculations provides us with information on the climatological precipitation distributions over moving windows. The comparison becomes therefore an assessment of the changes in the climatology between different 51-year periods. This climatology does not only provide information on the mean state but also further derived statistics, the extreme percentiles for the individual windows, and the ~~regional simulation appear to represent comparable evolutions. Whether this is a dynamical feature or an imprint of the forcing dataremains unclear~~variability in these periods.

If this climatology for the observations is the target climatology, an ensemble of climate simulations should sample this distribution interannually following the paradigm of a statistically indistiguishable ensemble (Annan and Hargreaves, 2011). Our analyses compare how well the climatologies agree in different sources of data.

6 Discussion

5.1 Data

Figure 2 gave slight indications of a positive relation between natural external climate forcings

5.1.1 Observations

Starting from the available regional climate simulation, we choose the region for our study based on the availability of precipitation observation and reconstruction data. There are long records of instrumental measurements of climate parameters for a number of locations in Europe. The British Isles are unique because there exist long observation based indices for precipitation and temperature in form of the England-Wales precipitation data (Alexander and Jones, 2000) and the Central England Temperature (CET) and of the absence of this link in simulations. As Frank et al. (2007) noted data (Parker et al., 1992) besides the long instrumental precipitation observations, e.g. in southern Great Britain, for Kew Gardens, Oxford, and Pode Hole. Additionally there are instrumental records from Inverness, Edinburgh, and Manchester starting in the 1780s, which we do not use because of their northern locations. For Ireland, Murphy et al. (2018) provide a monthly rainfall series starting in the year 1711, which we do not discuss here either because of its distance to our study region.

The Central England and England-Wales observation indices are good representations of the late 20th century climate of the South of Great Britain according to Croxton et al. (2006). Our Figure 2 also shows the strong correlation between the various precipitation records based on observations. Note that the composite series naturally rely on the instrumental series. Weakest relations occur for the instrumental series of Pode Hole with the sub-regional series for South-West England and for the relation between the two instrumental records from Pode Hole and Kew Gardens. Frank et al. (2007) noted the uncertainties in early instrumental temperature observationsare not without caveats. Additionally, the very early data in the CET Central England Temperature data includes non-instrumental indirect data to infer past temperature. Furthermore, the simulations use not only different parameterizations for precipitation but also different horizontal grids. This leads, besides dynamical implications, to different spatial representativeness of the grid-points considered for our regions. For example, MRI and CCSM4 approximate the British Isles well, whereas CSIRO has only a very crude representation. If we consider larger European domains, there appear to be more relations between sunspot numbers and temperature but a detailed analysis should consider the specific data used as solar forcing in individual simulations (compare Schmidt et al., 2011). In any case, a lack of an identifiable relation to the forcing does not necessarily imply that the underlying climate data arewrong but may simply suggest that internal natural climate variability dominatesSimilarly, early precipitation observations require rigorous quality control. In this context, Woodley (1996) reviews the history of England and Wales as well as Scotland precipitation data.

Figure 2 further shows the negative relation between temperature and precipitation for our domain of interest. Tout (1987) does not find any changes in the negative relation between England-Wales precipitation and Central England Temperature for the summer season from June to August between 1766 and 1980.

5.1.2 Reconstructions

Paleo-reconstructions of the recent past have made notable progress both in the spatial coverage and in the quality of the reconstructions by incorporating so far unexplored data sources and new methods. Küttel et al. (2010), for example, highlight the importance of ship-based observations recorded in log books for reconstructing large-scale fields. Initiatives like oldweather.org or ACRE (Atmospheric Circulation Reconstructions over the Earth, www.met-acre.org) are invaluable for such efforts and also aid reanalysis projects like the twentieth century reanalysis (Compo et al., 2011), the reanalysis of global fields for the period 1600 to 2005 by Franke et al. (2017), or the last millennium climate reanalysis (Hakim et al., 2016).

For the hydroclimate, there are a number of gridded reconstructions covering the European domain. Continental domain gridded precipitation reconstructions are, e.g., the atmospheric circulation masks, modulates, or counteracts an external forcing influence. Pauling et al. (2006), Casty et al. (2007), and Franke et al. (2017). Reconstructions of drought indices like the Palmer Drought Severity Index (PDSI) exist as gridded products, too, for various regions of the world including Europe (The Old World Drought At These products allow assessing the quality of the hydroclimate in paleoclimate simulations (Smerdon et al., 2015).

In turn, we do not necessarily expect the PMIP3 simulations The availability of observational data and regional reconstructions motivates our domain choice covering southern Great Britain. We decide to use regional precipitation reconstructions instead of gridded products to minimise the effect of the reconstruction method on the results. We focus on precipitation as it allows the direct comparison with long instrumental records and it is a parameter directly experienced by people.

We mainly focus on two reconstructions based on tree-ring widths measurements (Cooper et al., 2013; Wilson et al., 2013). These authors calibrate their tree-ring data against gridded precipitation beyond their target regions of Southern-Central England and East Anglia, respectively. Thereby the reconstructions are possibly biased beyond their respective regions of interest. They compare their reconstructions against the long instrumental records and find a lack of stability of the relation to the instrumental data. They discuss the limitations of their reconstructions representing less than 40% of the regional precipitation variance over the 20th century.

Although the reconstructions show a notable amount of low frequency variability, Cooper et al. (2013) cautions against too much confidence in the low frequency precipitation variability in their reconstruction. Wilson et al. (2013) and Cooper et al. (2013) emphas the weaknesses of their reconstructions in representing extreme years. On the other hand, both are confident in the mid- to agree on the evolution of England temperature even for the considered low frequencies since the considered spatial scale is small and the influence of natural internal variability high-frequencies of their reconstructions.

Both, Wilson et al. (2013) and Cooper et al. (2013) discuss the possibility that the tree-species used for their reconstructions were less sensitive to precipitation over certain periods, e.g., the North Atlantic Oscillation, is large (Gómez-Navarro et al., 2012; Gómez-Na 19th century. That is, while the forcing history suggests notable variations and large-scale temperature records indicate an imprint of the forcing history on hemispheric and global temperatures, internal variability may dominate on smaller regional scales (e.g., Deser et al., 2012b). Thus, again, differences among the various PMIP3 simulations and between the simulation ensemble and observations, reconstructions, and a regional simulation may simply signal the overwhelming influence of the internal variability. proxies, theoretically representing a precipitation signal, also contain a temperature signal, for instance, if they are sensitive to soil moisture. Wilson et al. further suggest an effect of the Industrial Revolution and the associated pollution on the trees in their selection. Wilson et al. (2013) also discuss the reliability of the instrumental data but conclude this is likely not an issue.

Consistent variations in precipitation distribution properties would increase our confidence in forced changes, but the PMIP3 simulations also disagree there as could have been expected a priori. While the disagreement in temperature already suggests the lack of consistent signals within the ensemble, the lacking agreement in the relation between regional temperature and regional precipitation is unfortunate. Although Fischer et al. (2014) show that forced signals can agree in the CMIP5 21st century projections, the lack of consistent relations under purely externally naturally forced and internal variability on multi-decadal time-scales questions our ability to make dynamical inferences about climate variability of small regions in Besides these two tree-ring width based reconstructions, the PMIP3 ensembleworks by Rinne et al. (2013) and Young et al. (2015) use $\delta^{18}O$ data to reconstruct precipitation for Southern England and Great Britain respectively. We shortly discuss results for both reconstructions below. Rinne et al. (2013) calibrate and scale their local isotope data from 1613 to 1893 CE against the station observations from Oxford for the period 1815 to 1893 CE and concatenate the reconstruction with the observations for 1894 to 2003 CE. They target an extended summer season from May to August. Young et al. (2015) use the England-Wales summer, June to August, precipitation as scaling target for a composite of eight isotope records from Scotland, Wales, and England for the period 1766 to 2012 CE. Both publications by Rinne et al. (2013) and Young et al. (2015) note the differences of their reconstructions to the tree-ring width based works by Wilson et al. (2013) and Cooper et al. (2013).

While the regional CCLM simulation shows some agreement with the observations over the period of the England-Wales Precipitation there are still notable disagreements in the relation between regional temperature and regional precipitation in the median of Young et al. (2015) conclude that these differences make it unlikely that the tree-ring based works and their $\delta^{18}O$ based work represent the same environmental parameter, and they emphasize the lack of a calibration against regional precipitation data. They further discuss the reasons given by Wilson et al. (2013) for the lacking stability of the dataWilson et al. reconstruction, namely, different climate-sensitivity of the trees, unreliable instrumental data, and pollution. Young et al. (2015) conclude that their own data reliably reflects precipitation while the tree-ring widths most likely represent the combination of various environmental influences on tree growth instead of a single climate parameter.

5.1.3 Simulations

In contrast to present-day and future scenario regional simulations, the 0.44 by 0.44 degree resolution of our CCLM simulation represents a comparatively coarse resolution dynamical downscaling. Sørland et al. (2018) discuss how the use of a model-chain including global and regional climate simulations assists studies on regional climates. Besides other models, they also use CCLM in a 50km setup comparable to the simulation used here. Their work emphasizes that improved representation of regional climate in a regional simulation is not solely due to the increased resolution but may be due to different strategies in model-building and tuning. Pinto et al. (2018) study global and regional simulations, including CCLM-simulations, for southern Africa. They explain differences in results from regional and global simulations by an interplay between the representation of sub-grid-scale processes in the different models and factors related to the increased resolution. Blenkinsop and Fowler (2007) note that regional climate models may be deficient in their ability to model persistent low precipitation episodes for the British Isles, which has repercussions for their representation of drought events. The observational period is still too short to assess the reliability of the simulation in the Late Maunder Minimum period. Since our regional focus is close to the western boundary of the domain of the regional simulation, we expect a rather strong influence of the dynamical evolution of the driving coarse-resolution simulation with MPI-ESM-COSMOS. We have to emphasize that the

The review by Ludwig et al. (2018) reports more realistic distributions for precipitation in regional paleoclimate simulations. Flato et al. (2013, chapter 9 of the IPCC AR5) review the progress of regional downscaling and high-resolution modelling. They emphasize that the skill of such exercises depends on the model used, the season, the domain of interest, and the considered meteorological variable. They highlight studies showing that there is not a linear increase in simulation skill towards higher resolutions. Higher resolutions typically provide more reliable estimates of extremes, including heavy rainfall. Flato et al. (2013) view regional modelling as a valuable extension of global climate modelling.

The quality of the simulated precipitation still strongly depends on the parameterisations implemented in the regional simulation climate model. Precipitation, especially convective precipitation events, are still sub-grid processes, even within regional climate models. Concentrating on accumulated amounts on seasonal time-scales and their long-term changes, however, allows at least a more robust comparison of simulated precipitation to observed and reconstructed data.

Shortcomings of the various data sets limit our expectations to what extent they can reflect comparable variations among each other.

5.2 Discussion of Results

5.2.1 Validity of approach

Information from reconstructions of climate parameters and from simulation output together increase our understanding of past climates. The PAGES Hydro2k Consortium (2017) made recommendations for valid and appropriate comparisons of hydroclimate data from both sources of information. Here, we consider approximately the last 350 years by comparing both estimates to long instrumental data. We have to consider whether our analyes are appropriate in the sense of the recommendations concerning uncertainties, the properties compared, and the expectations underlying the comparison (PAGES Hydro2k Consortium, 2017).

The observational England-Wales precipitation data is a weighted composite of regional series which again are based on instrumental information. The input changed over time. Similarly, the reconstructions combine spatially distributed proxy, e.g., tree-ring width series into regional scale composite series (Cooper et al., 2013; Wilson et al., 2013) to maximise the common signal between different locations. On the other hand, the simulations are aggregations of various grid-point time series from the simulation output. We assume that the compositing and the aggregation have similar effects in removing local variability. In this respect, records from different sources are similar to each other and thus our comparison appears valid.

Explicit uncertainty estimates are only available for the reconstruction for East Anglia and only for a low-pass filtered version of the data (Cooper et al., 2013). Our results as well as the discussions of Cooper et al. (2013), Wilson et al. (2013), Rinne et al. (2013), and Young et al. (2015) emphasize that uncertainties for the reconstructions are potentially large and that even the relation to precipitation is not necessarily valid for parts of them. Similarly, uncertainties affect the simulations not only with respect to our domain choice but also with respect to the algorithms and parametrisations implemented for simulating precipitation in the regional climate model.

Considering the limitations of the simulation and the a priori known shortcomings of the reconstructions, questions may arise on the validity and robustness of our analyses. We argue that the transformation to standardized indices provides a sound basis for equivalence between the different precipitation estimates for subsequent comparisons of the distributional properties.

Then, we assume that the comparison becomes informative for changes over time between these distributions. While we cannot expect accurate or even approximate temporal agreement between time series from simulation output and observation based data on either interannual or multi-decadal time-scales because of internal variability, the transformation makes our comparison one of climatologies. Furthermore, one may assume that the evolution of percentiles and variability may be more consistent between the different data sets than the average conditions.

5.2.2 Additional analyses

We find that the considered observations, reconstructions, and a regional simulation only show limited agreement in their representation of precipitation for a small regional domain covering southern Great Britain for approximately the last 350 years. Striking are the differences between the tree-ring width based reconstructions (Cooper et al., 2013; Wilson et al., 2013) and the observations, which again highlight the shortcomings of the two considered reconstructions (compare Young et al., 2015). It is noteworthy that there are multiple periods where simulation output and reconstructions evolve oppositely. Possibly surprising is occasional temporal consistency in some of the measures between regional simulation and its driving MPI-ESM-COSMOS simulation both use variations of the total solar irradiance forcing that could be unrealistically wide. Furthermore, neither simulation includes a resolved stratosphere to account for potential UV-related top-down mechanisms (Anet et al., 2013, 2014). Thus, while the simulation appears to present similar variations England-Wales precipitation data.

We performed similar analyses on a selection of the PMIP3-ensemble of global simulations (Schmidt et al., 2011). There, we see no commonalities between the different simulations or the simulations and the other sources of information in the analyses of precipitation distribution properties (not shown, see supplementary manuscript asset).

If we use different reconstructions, agreement between simulation and reconstructed precipitation does not necessarily increase, but differences between reconstructions and observations may be reduced (not shown, see supplementary manuscript asset). We use two different reconstructions based on $\delta^{18}O$. For one, we obtain the precipitation reconstruction by Rinne et al. (2013) for Southern England for the May to August extended summer season. Secondly, we use the isotope records for England and Wales by Young et al. (2015) and scale the composite against the observational England-Wales precipitation data. We follow the procedure described by Young et al. (2015) but for two seasonal estimates, the extended spring from March to July used in our main analyses and, following Young et al. for the summer season from June to August. See the supplementary manuscript asset for some details of the comparison to the summer scaling.

For the scaled data by Young et al. (2015), the most striking feature is again a notable difference in the percentiles prior to time windows approximately centered in the year 1850 compared to the observations, it is unclear whether it does so for the right reasonslater period. This feature resembles the behavior of the tree-ring width based reconstructions. While this may be due to the chosen calibration method and period, it appears more likely that there is a problem in the relation between isotopes and precipitation for this early period. Comparing the data to the extended spring observations, there is limited agreement for the dry percentile after this early period (not shown). For other periods, the moving window distributions show prominent inconsistencies compared to their observational counterparts. Comparing the data by Young et al. to the regional simulation also does not show any agreement.

The period covered by the data of Rinne et al. (2013) only shortly overlaps with the period of the observational data. For this overlap dry percentiles tend to agree with the observations but wet percentiles evolve oppositely (compare supplementary manuscript asset). The change in average precipitation for a reference year also agrees between both data sets for the time of overlap (not shown). Compared to the regional simulation output, evolutions tend to be opposite.

5.2.3 Implications of main results

Our analyses highlight the shortcomings of different reconstructions relative to observations. We also see that differences to observations may be comparable for reconstructions and simulations. Our methods also show that apparently the reconstructions and the simulations frequently evolve differently. This may signal that we indeed do not perform a valid comparison, that simulations may misrepresent forced responses, or, considering the reconstructions' relation to temperature, that the reconstructions do not fully relate to precipitation.

We expect disagreement between simulations and observations on some levels, not least because of differing influences of internal variability (see discussions below). More critical appears is the lack of consistency between reconstructions and observations. Most notably the reconstructions show unrealistically large changes in the cumulative probabilities represented by certain precipitation amounts (compare Figure 1Figures 7 to 9). The reconstructions do not reliably represent the distributions in specific periods. They possibly only reflect the low-frequency changes in the mean plus a certain amount of noise. Plotting the anomalies for the observations and reconstructions (not shown) displays much stronger variability over the common period in the reconstructions compared to the observations and at times opposite trends.

Cooper et al. (2013) and Wilson et al. (2013) found good correlation skill for their East Anglia and Southern-Central England data respectively. They showed the results for interannually resolved data . Here we present relations for multi-decadal running measures. While the median-precipitation-temperature relation agrees between observations and reconstructions over recent periods, the reconstructions suggest a more stable relation than in the observations in early periods and a breakdown of the relation in Southern-Central England recentlyOne result is the inconsistency of the relations between temperature and precipitation in the data sets for the considered domains. Tout (1987) and Crhová and Holtanová (2018) both note the negative relation between temperature and precipitation observations for Britain. We find this only consistently in the simulation, and over the more recent period in the observations. The tree-ring width based reconstructions do not show any clear relation for the extended spring season. If we consider other seasons, the disagreement between data sets changes (not shown). The observations show consistently negative correlations for the summer season, and the scaled isotope data by Young et al. (2015) agrees quite well with the summer observations except for a large part of the 20th century when it shows a markedly weaker negative correlation (not shown). The simulation shows again generally stronger correlations compared to the other data in summer and shows some agreement with the observations in the industrial period since approximately the year 1850 (not shown). If we correlate the scaled isotope data to the temperature for an extended spring season from March to July, the correlations are quite similar to those for the larger domain simulation output but differ notably from the observations (not shown). The extended summer (MJJA) reconstruction by Rinne et al. (2013) agrees well with the respective observations in a consistently negative correlation (not shown). The relation is weaker for the reconstruction prior to the period of the Oxford precipitation observations (not shown).

Explanations for the different temperature-precipitation relations might be either physical inconsistencies within the simulations or a lack of physical relation between the temperature and precipitation records. A third possibility is that internal large-scale climate factors influencing the relation between both parameters evolve differently in simulation and reality. This implies a dominant influence of internal variability on the considered regional and temporal scales which we discuss in the next sub-section. Even though reconstructions and observations represent different regional domains, we tend to the inference that the disagreement between the observations and reconstructions ~~suggest~~ suggests major shortcomings in the reconstructions, if we ~~view the observations as~~ assume the observations to be the more reliable data set.

~~Both Wilson et al. (2013) and Cooper~~

5.2.4 Internal vs. forced variability

If we look for temporal consistency among different source of informations, we assume that all sources of information reflect similar impact of the external climate forcing. Moreover, we then also believe the regional simulation to be skillful in representing the climate response to these conditions. We also have to be aware that internal climate variability may dominate even for large exogenous forcing (compare, e.g. Deser et al., 2012a). We can frame this as the question to what extend one can expect simulations and observation based data sets to reflect consistently these exogenous influences.

We assume that the transformation to distributional properties smooths out some of the temporal and structural differences from the different evolutions of internal variability expected between simulations and observational data. However, influences from low frequent climate modes may still have different phases in different data sets. In this sense, it is encouraging that the regional simulation shows some commonalities with the observed statistics.

The instrumental period overlaps with the industrial period of large anthropogenic climate forcing. Earlier in our period of interest exogenous forcing is potentially weak. However the period includes periods of relatively large variations in solar activity like the late Maunder Minimum (~1645 to ~1715 CE), the Dalton Minimum in the early 19th century, and a period with relatively strong solar activity inbetween as indicated by sunspot numbers (Clette et al., 2014). Furthermore, a number of strong tropical volcanic eruptions occurred during this period, i.e. in ~1809 CE (unknown location), 1815 CE (Tambora), and 1835 CE (Cosigüina) (e.g., Schmidt et al., 2011).

Fischer et al. ~~(2013) already discuss the possibility that the tree-species used for their reconstructions were less sensitive to precipitation over certain periods,~~ (2014) show that forced precipitation signals can agree in the CMIP5 21st century global projections. The lack of consistent relations between different data sets under purely externally naturally forced and internal variability on multi-decadal time-scales questions our ability to make dynamical inferences about hydroclimate variability of small regions.

A lack of an identifiable relation to the forcing does not necessarily imply that the underlying climate data are wrong but may simply suggest that internal natural variability dominates, e.g., oceanic, atmospheric, or coupled climate variability mask, modulate, or counteract an external forcing influence. That is, the lack of consistent evolutions points to shortcomings of the data sources or an overwhelming influence of internal variability. The sporadic opposite behavior make the first more likely without negating the latter. That is, we interpret the opposite behavior as reactions to the forcing but different reactions of simulated and observed climate.

In this context, we have to emphasize that the regional simulation and its driving MPI-ESM-COSMOS simulation both use variations of the total solar irradiance forcing that could be unrealistically wide. Furthermore, neither simulation includes a resolved stratosphere to account for potential UV-related top-down mechanisms (Anet et al., 2013, 2014).

Furthermore, since our regional focus is close to the western boundary of the domain of the regional simulation, we expect a rather strong influence of the dynamical evolution of the driving coarse-resolution simulation with MPI-ESM-COSMOS. Indeed, Blenkinsop and Fowler (2007) report a strong influence of the driving general circulation model on the representation of drought in regional climate simulations in southern Great Britain.

Thus, while the regional simulation appears to present similar variations compared to the observations during some periods, it is unclear whether it does so for the right reasons.

5.2.5 Relation to dynamics

Our regional focus is a small domain. Thus, we should not expect simulations to agree with observations on the evolution of regional climate parameters and even an ensemble may show diverse behavior since the influence of natural internal variability is large, e.g.~~, the early 19th century. Wilson and colleagues further suggest an effect of the Industrial Revolution and the associated pollution on the trees in their selection~~ in the case of the British Isles, the North Atlantic Oscillation (Gómez-Navarro et al., 2012; Gómez-Navarro and Zorita, 2013). Bengtsson et al. (2006) note the general importance of the storm track over the North Atlantic as a control on precipitation variability, and Dong et al. (2013) show this for the England-Wales summer season precipitation. Hall and Hanna (2018) study to what extent North Atlantic circulation indices explain precipitation in the United Kingdom. They note a negative correlation of summer precipitation with indices representing jet-latitudes, which include the NAO. Blackburn et al. (2008) detail the large-scale influences, e.g., the wave-train pattern on the jet stream, on the flooding events in the UK in 2007. Earlier, Kington (1990) noted the strong relation between the England-Wales precipitation and Lamb's cyclonic British Isles weather type (compare, e.g., Lamb, 1950) in spring, while recently Matthews et al. (2016) emphasize the importance of the high-frequent weather variability, i.e. cyclones, for seasonal precipitation amounts over the British Isles and particularly the summer season.

We note that Cooper et al. (2013) do not find any significant influence of the North Atlantic Oscillation (NAO) on precipitation or tree growth in East Anglia over the 20th century. They use the NAO as a measure of large scale influences on western European precipitation coherence.

Thus, internal climate variability is an integral expression of the circulation over the North Atlantic region. Differences in internal variability between models, observations, and paleo-observations may also include instabilities of dominant large scale patterns. That is, we cannot reject the idea that the relationship between regional climate and the large-scale circulation changed in the past. Lehner et al. (2012) describe the importance of such changes for inferring past states of the North Atlantic Oscillation from sparse proxy data. The importance of changes in the large-scale circulation becomes even more clear when considering the stability in centers of action in the North Atlantic sector or rather the lack of stability over longer time-scales (Pinto and Raible, 2012; Raible et al., 2014).

For That is, while the forcing history suggests notable variations and large-scale temperature records indicate an imprint of the forcing history on hemispheric and global temperatures, internal variability may dominate on smaller regional scales (e.g., Deser et al., 2012b). This is despite the fact that, e.g., the large scale storm track is indeed sensitive to solar (e.g., Ineson et al., 2015) an volcanic forcing (e.g., Fischer et al., 2007; Trouet et al., 2018). Considering the possibly large role of internal variability on regional scales and the limitations of simulations in representing regional scale precipitation, the occasionally consistent variations in precipitation distribution properties increase our confidence in forced changes.

5.2.6 Concluding remarks

In summarising, for the chosen regional domains, we do not find consistency among the various data sets. However, each of these data sets is associated with its own uncertainties, which put various caveats on the interpretation of the lacking consistency and its sources. Encouragingly simulations and observations appear to agree on certain features occasionally but maybe for different reasons.

6 Conclusions

Our objective in this study was to identify consistent signals in the variations of precipitation as represented by observations, reconstructions, and This study pursued two goals. For one, we wanted to show that comparing precipitation in reconstructions, climate model simulationsfor the last 350 years. We chose , and observations based on the Standardized Precipitation Index (SPI) over moving windows allows for the rigorous comparison of these data sets and extends the common set of tools for such analyses. Second, by using this approach, we studied the consistency of the various sources of information for precipitation variations in a small regional domainover the British Isles . We chose a domain in southern Great Britain and compared long-term trends, decadal variability, and the probability distribution. Standardisation of precipitation data allowed going

~~beyond comparing means and expectations of deviations from the mean. We also specifically looked for co-variability between precipitation and temperature within the various data sets~~distributions for the period since approximately 1650 CE.

Fitting distributions over moving windows provides the opportunity to compare how the different sources of information represent various percentiles and moments of the distributions over time in the presence of varying external forcings. It further allows to compare which percentile a reference precipitation amount represents over time; more loosely spoken, one compares how the probability of a reference precipitation amount changes over time.

For our specific study domain, we did not find any clear common consistency for precipitation signals among a ~~multi-model ensemble of global simulations, a regional~~ regional climate model simulation, an observational data set, and two local domain reconstructions. The ~~global simulations show a wide range in the trajectories of precipitation, the relations between regional temperature and precipitation, and the precipitation statistics. The~~ regional simulation shows only limited agreement with its observational target but less so with the reconstructions. ~~However, the~~ The considered reconstructions indeed appear to be unreliable representations of the observational series. ~~In turn, we cannot find common signals in precipitation among the different data sets.~~

~~One of the most concerning results is the inconsistency of the relations between temperature and precipitation in the data sets for the considered domains on decadal to centennial time-scales. Explanations might be either physical inconsistencies within the simulations or a lack of physical relation between the~~ Relations between temperature and precipitation ~~records. A third possibility is that internal large-scale climate factors influencing the relation between both parameters evolve differently in simulation and reality. Again, this implies a dominant influence of internal variability on the considered regional and temporal scales. However, relations~~ share some common co-variance on ~~the interannual and decadal time scales~~ interannual time scales between the sources of information.

~~Another important~~ A further interesting result is the at times opposite evolution of the reconstructions and the regional simulations ~~in~~ considering regional dryness and wetness. However, we ~~are not able to~~ cannot attribute it to the external forcing or to errors in either data source. ~~Furthermore, the~~ The partial agreement between variability and dryness of the regional simulation and observations is encouraging but may be due to different processes in the respective data ~~source.~~ sources.

Generally, a dominant role of internal variability could explain the lack of consistency in standardised precipitation measures in the different data sets on the temporal and spatial scales we consider here; the relative role of the external climate forcing generally becomes ~~smaller at diminishing spatial and~~ weaker at smaller spatial and shorter temporal scales (Deser et al., 2012b). ~~However, the differing~~ The lack of general consistency and slightly differing interannual relations between temperature and precipitation still require a closer look at the uncertainties of observations, the methods and input data of reconstructions, and dynamical and thermodynamical representations of regional climate in regional and global simulations.

A supplementary asset for this manuscript will be deposited at https://osf.io/duyqe/.

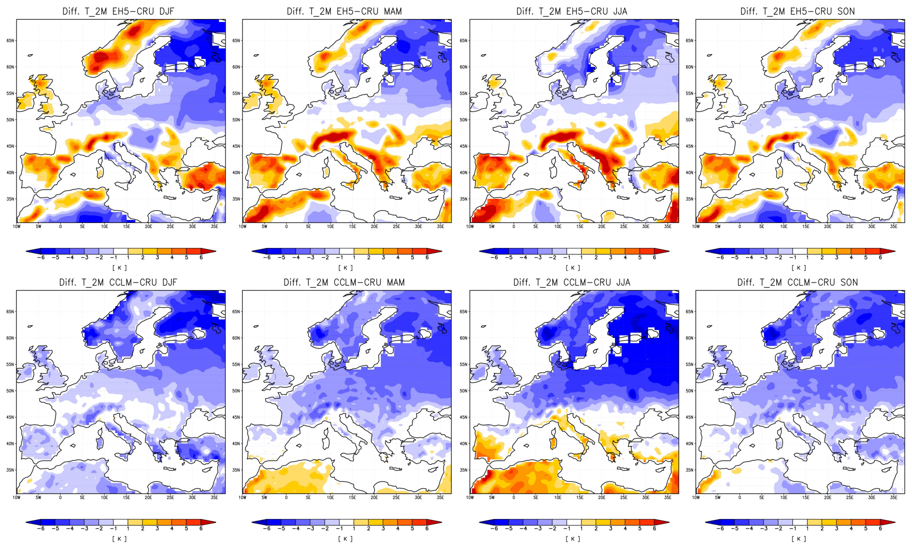


Figure A1. Top: Difference between the driving MPI-ESM simulation and the CRU data for seasonal near surface air temperature. Bottom: Difference for CCLM

Data availability. The Central England Temperature data is available from the Met Office, https://www.metoffice.gov.uk/hadobs/hadcet/.

The England-Wales Precipitation data is available from the Met Office, https://www.metoffice.gov.uk/hadobs/hadukp/ as are the subdivisions for South-East, South-West, and Central England.

Station data for Oxford, Kew Gardens and Pode Hole is available at, e.g., the Climate Explorer (http://climexp.knmi.nl/) of the Koninklijk Nederlands Meteorologisch Instituut (KNMI).

The reconstruction data for Southern-Central England and East Anglia are available from the NOAA National Centers for Environmental Information at, respectively, https://www.ncdc.noaa.gov/paleo-search/study/12907 and https://www.ncdc.noaa.gov/paleo-search/study/12896.

Temperature and precipitation fields from the regional simulation with CCLM are available at http://doi.org/10.6084/m9.figshare.5952025 (PRIME2, 2018).

If deemed relevant for future work, we are going to provide the standardised data as well via a public repository.

Appendix A: Evaluation of the simulation setup against the CRU-data

We shortly describe the performance of the COSMOS-MPI-ESM-CCLM-setup compared to the observational CRU-data ~~(Harris et al., 2014)~~(Harris et al., 2014; University of East Anglia Climatic Research Unit et al., 2017). We used version CRU TS 3.10, which has subsequently been superseded. The current version CRU TS 4.01 is available at http://doi.org/10/gcmcz3 with further information also given at https://crudata.uea.ac.uk/cru/data/hrg/ (last visited 20 September 2018).

The mean climate of the driving COSMOS-MPI-ESM simulation is too warm for much of the British Isles~~(Figure A1, top)~~, the Scandinavian Alps, northern North Africa, Iberia, the Alps, southern France, Turkey, and Greece for all seasons over the period 1951-2000 (Figure A1, top). It is generally too cold over the Baltic region, the eastern part of the model domain, the

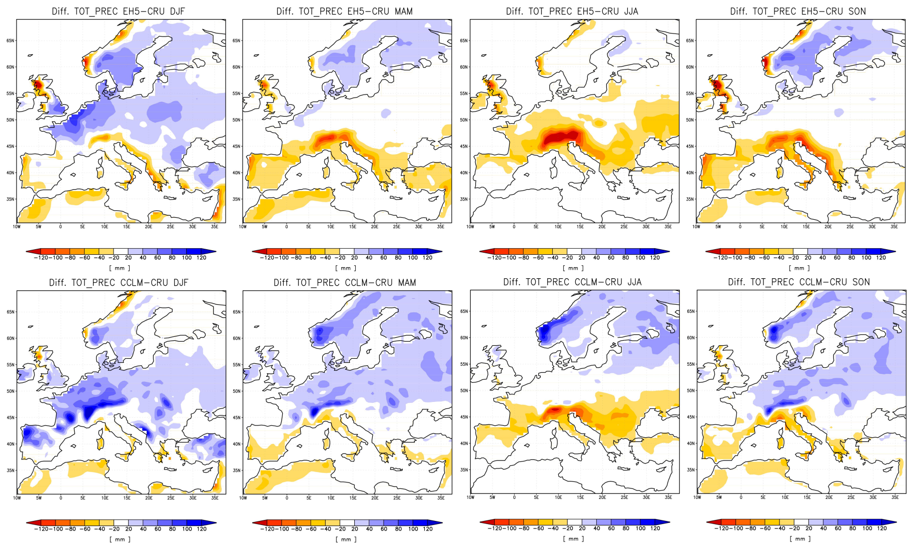


Figure A2. ~~Top: Difference between the driving MPI-ESM simulation and the CRU data for seasonal near surface air temperature. Bottom: Difference~~ As Figure A1 but for ~~CCLM~~the precipitation

southern border of the domain over Africa, and central Europe. High elevation and southern area warm biases frequently exceed 6K. Cold biases exceed 2 to 4K occasionally over northeastern Europe and at the southern border of the domain. We attribute these biases to some extent to the cruder representation of the European orography and, possibly related to that, to biases in the modelled atmospheric circulation. However, the specific choice of forcings may also influence the climatology.

In the regional CCLM simulation (Figure A1, bottom), warm biases for 1951-2000 are confined to the Atlas Mountains in all seasons and to the ~~south~~ South of the domain in spring and summer. Cold biases are common otherwise and are largest over the Northeast frequently exceeding 3-4K.

~~As Figure A1 but for the precipitation~~

~~Considering~~ For precipitation, summer is frequently too dry in central Europe in COSMOS-MPI-ESM and especially at the west coast of Scotland and in the Alps (Figure A2, top row). The southern domain is generally too dry in spring when Scandinavia is slightly too wet. Coastal and mountainous regions as well as Iberia, Italy, and southern France are more likely to be too dry in autumn and winter. Scandinavia is also too wet in autumn. The COSMOS-MPI-ESM winter climatology is too wet over much of central, eastern, and northern Europe.

In CCLM, too dry conditions are generally confined to southern Europe and North Africa and areas affected by the storm track, i.e. the coasts of Scotland and Norway (Figure A2, bottom row). They extend to southern central Europe only in summer. The climate is too wet in Scandinavia and northeastern Europe in most seasons. Large parts of Europe are too wet in all seasons except summer. Noteworthy is the excess precipitation at the northern flank of the Alps from autumn to spring. Part of these discrepancies are possibly attributable to a too zonal airflow outside the summer season.

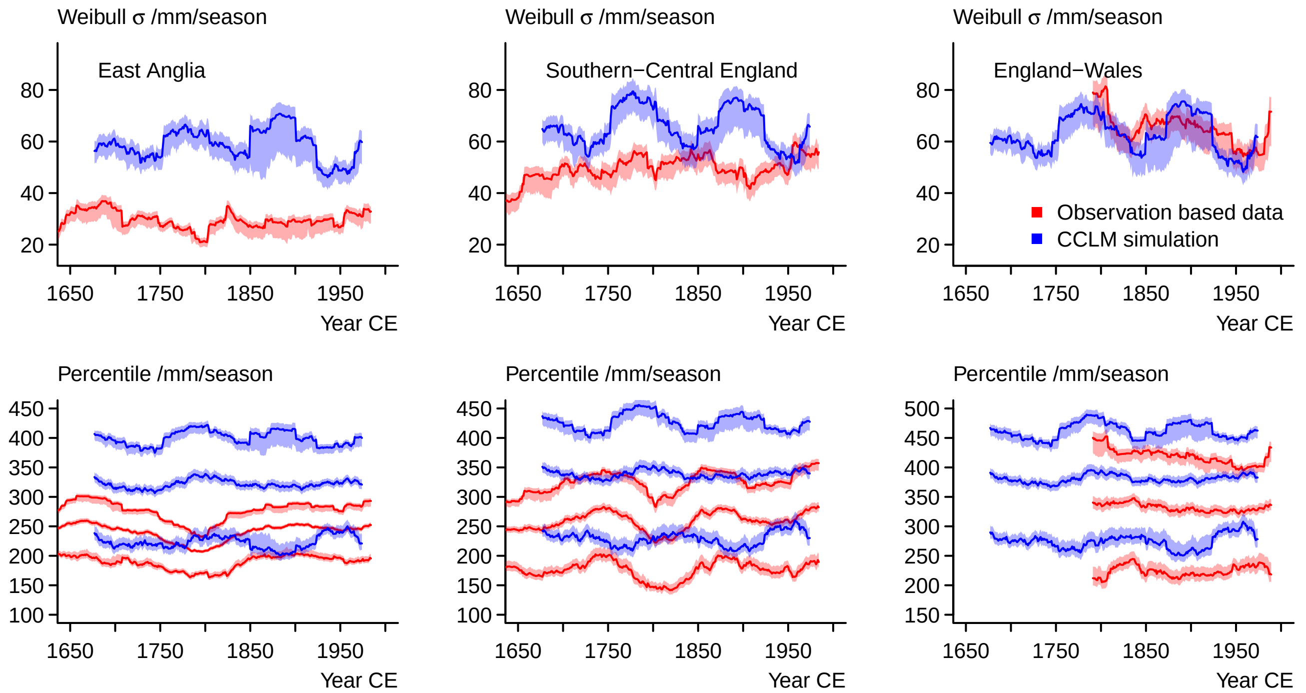


Figure B1. ~~Visualisations~~ Visualisation of uncertainty of the distributional properties. We use a bootstrap procedure on running estimates~~with 1000 resamplings of~~. We resample 40 year samples a thousand times from ~~each window; units~~ moving 51-year windows. Units are precipitation amounts. Shading are 95% intervals, lines are medians. Top row: Weibull standard deviation. Bottom row: 93.3th, 50th, and 6.7th percentiles. Red: Reconstruction and observations. Blue: CCLM. The left column is for East Anglia, the middle column for Southern-Central England, and the right column for the England-Wales precipitation.

In summarizing, the model presents a too strong latitudinal temperature gradient over the European domain. The annual cycle of temperature is apparently too strong in the South with warm biases in summer but cold biases in winter and it is slightly too weak in the North with cold biases being stronger in summer than in winter. Similarly to temperature, the gradient in precipitation also appears to be too strong and the annual cycle amplitude differs between simulation and gridded observational estimates especially for Central Europe. Specifically, autumn to spring are wetter in the simulation while summer conditions differ only slightly or are too dry, which implies a weaker annual cycle compared to observations.

Appendix B: Uncertainty of running measures

Figure B1 shows bootstrap estimates over thousand 40-year samples for each 51-year window. The estimates are for the running measures for reconstructions and observations for the three regions of interest (red) and the regional simulation (blue). The top row are Weibull standard deviations and the bottom row is for the percentiles.

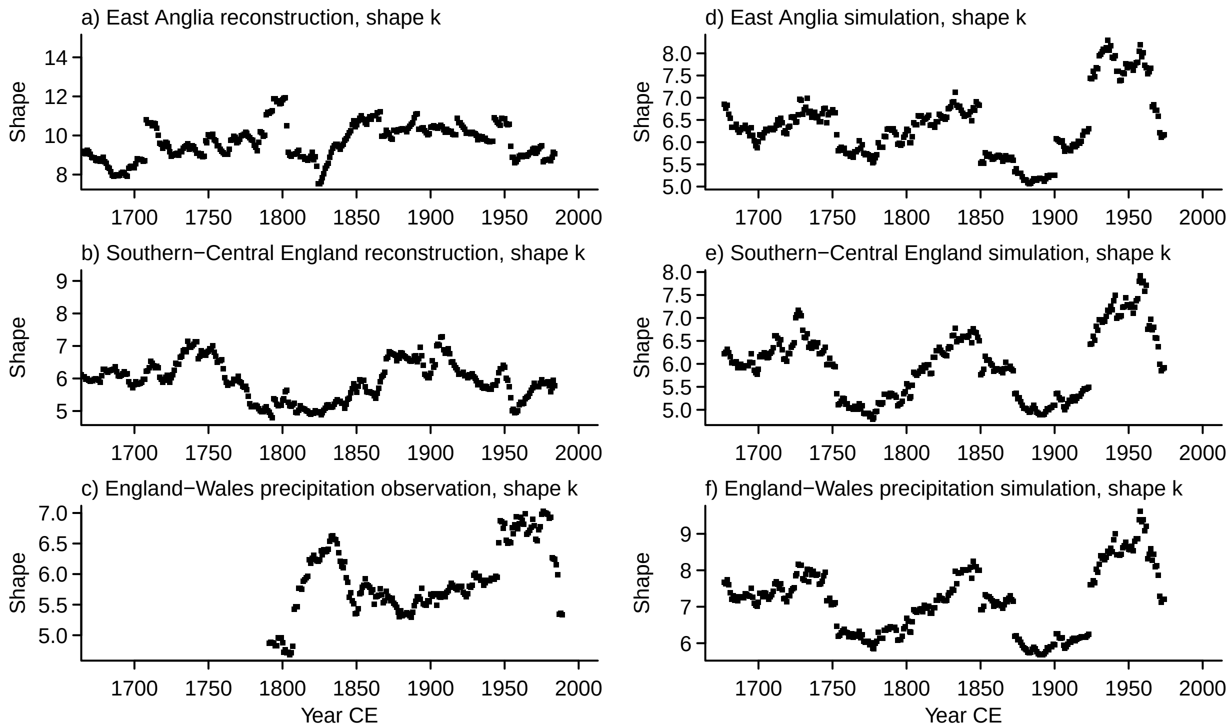


Figure C1. Evolution of the shape parameter k for the Weibull distribution fits for the a) East Anglia reconstruction, b) Southern-Central England reconstruction, c) England-Wales precipitation observational data, d) East Anglia regional simulation, e) Southern-Central England regional simulation, f) England-Wales precipitation regional simulation.

The Figure highlights that sampling variability is generally larger for the simulated data. Indeed sampling variability ~~generally but especially in the observed and reconstructed data~~ may render differences between periods non-significant. However, also the bootstrap distributions appear strongly skewed.

Appendix C: Distributional parameters

The Weibull distribution is a two parameter distribution with a scale and a shape parameter. See, e.g., Sienz et al. (2012), for more details and how the distribution compares to other distributions in computing the Standardised Precipitation Index.

Figures C1 and C2 present the shape, k, and scale, λ, parameters of our Weibull distribution fits for the reconstructions for East Anglia and Southern-Central England, the observational England-Wales precipitation, and the respective time series in the simulation.

Results for the simulation show very similar evolutions among regions highlighting the homogeneity of the simulation data. There are also similarities between the two reconstructions. One could argue the shape parameters evolve similarly in observation and simulation.

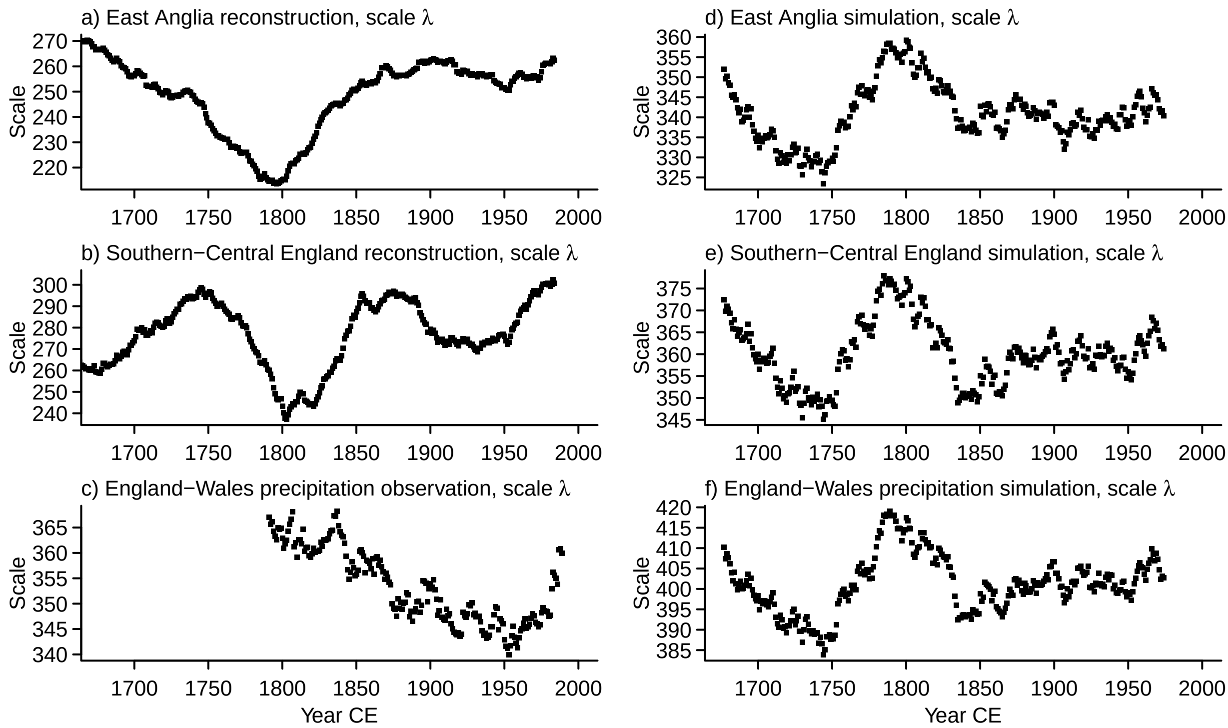


Figure C2. Evolution of the scale parameter λ for the Weibull distribution fits for the a) East Anglia reconstruction, b) Southern-Central England reconstruction, c) England-Wales precipitation observational data, d) East Anglia regional simulation, e) Southern-Central England regional simulation, f) England-Wales precipitation regional simulation.

The shape parameter determines the 'shape' of the distribution. In our cases, changes in this parameter are rather small (compare Figure C1). Nevertheless they can result in notably different widths of distributions for a specific data set over time. It is interesting that there is only small overlap between the range of shape parameters for the East Anglia reconstruction and all other series.

Larger scale parameters for a constant shape parameter result in a flatter distribution that extends further to larger values. Smaller values result in a narrower distribution with larger probability density at its peak.

The evolution of the shape parameter reflects, in our cases, the evolution of the skewness of the distributions (not shown). All distributions show negative skewness, and the amplitude increases with increases in the shape parameter.

Figure C3 shows the excess kurtosis over the period of interest. The most common feature for the different records is a negative excess kurtosis. Interestingly, the East Anglia reconstructions shows large positive values. The simulation data has a period with positive, or for the simulated England-Wales precipitation larger positive, values in the middle of the 20th century, and the observed England-Wales precipitation shows only negative excess kurtosis. The scaling of the kurtosis-axes for the reconstructions highlights that they show much larger values earlier in the last millennium (not shown, compare the supplementary manuscript asset).

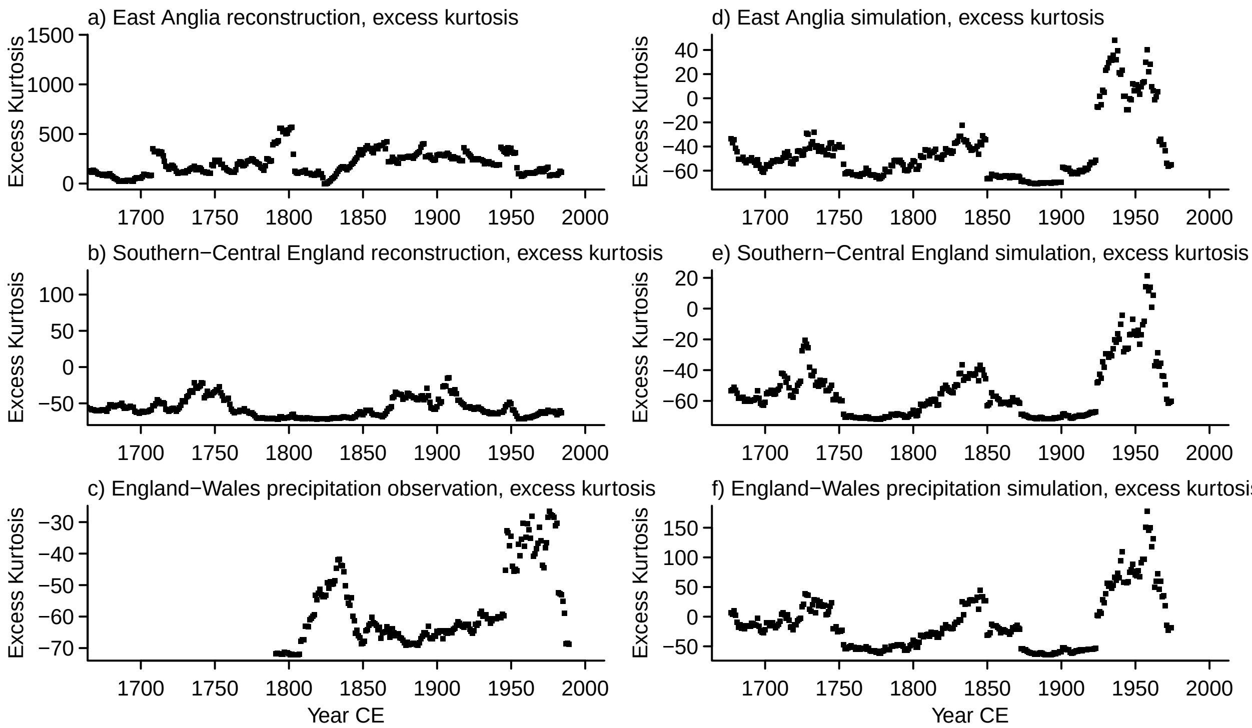


Figure C3. Evolution of the excess kurtosis of the fitted Weibull distributions for the a) East Anglia reconstruction, b) Southern-Central England reconstruction, c) England-Wales precipitation observational data, d) East Anglia regional simulation, e) Southern-Central England regional simulation, f) England-Wales precipitation regional simulation.

Appendix D: External code

This manuscript uses a number of external software-packages. File-manipulations used the Climate Data Operators (cdo, https://code.mpimet.mpg.de/projects/cdo/). Furthermore, the following R (R Core Team, 2018) packages helped in the work: gtools (Warnes et al., 2018), corrplot (Wei and Simko, 2017), ncdf (Pierce, 2015), VGAM (Yee, 2015), MASS (Venables and Ripley, 2002), nortest (Gross and Ligges, 2015), dplR (Bunn et al., 2018), zoo (Zeileis and Grothendieck, 2005), latex2exp (Meschiari, 2015), knitr (Xie, 2015), and rmarkdown (Allaire et al., 2018). Furthermore, RStudio (RStudio Team, 2016) was essential. The manuscript was prepared using the rticles-package (no reference available).

The SPI-code bases on work by Frank Sienz (e.g., Sienz et al., 2012). Christian Zang provided a Gershunov-bootstrap procedure (compare, e.g., Gershunov et al., 2001; Zang and Biondi, 2015) that we modified.

Competing interests. The authors are not aware of any circumstances that might be seen as competing interests.

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