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Climate of the Past Discussions

Inconsistencies between observed, reconstructed, and simulated precipitation over the British Isles during the last 350 years

Oliver Bothe[1], Sebastian Wagner[1], and Eduardo Zorita[1]

[1]Helmholtz Zentrum Geesthacht, Institute of Coastal Research, 21502 Geesthacht, Germany

Correspondence: Oliver Bothe (ol.bothe@gmail.com)

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 and long observational records of seasonal 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 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 not consistent among reconstructions, simulations, and instrumental observations regarding the probability distributions' changes in the quantiles for severe and extreme dry or wet conditions and 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.

Our results emphasize the complexity of changes in the hydroclimate 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.

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Consilience of evidence increases the robustness of estimates of future changes, which for precipitation are still highly uncertain in particular 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).

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, 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 (https://eip.ceh.ac.uk/droughts) 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 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.,

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Climate of the Past Discussions Open Access EGU

2010; Pauling et al., 2006; Leijonhufvud et al., 2010; Ahmed et al., 2013). 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.

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 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).

Common problems in comparing precipitation simulated with climate models and target data relate to pronounced biases in the simulated precipitation, especially derived from raw global models, and differences in representation or, in the case of data fields, the grid resolution. In the context of long observational time-series, data inhomogenities 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 precipitation to 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) stress 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 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 season.

The PAGES Hydro2k Consortium (2017) developed recommendations for the comparison of hydroclimate data from simulations and paleo-observations emphasizing the uncertainties of both sources of data. 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 represent the same parameters on related spatial and temporal scales. 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 gap. Proxy system models (Evans et al., 2013; PAGES Hydro2k Consortium, 2017) are one means to achieve this. We argue that the standardisation of precipitation data is another simple means to compare the statistical properties of hydroclimate in simulations and paleo-observations complementing the current suite of statistical diagnostics for model-data comparisons.

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 precipitation variability on the British Isles also benefits from recent reconstructions of 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 focus is on precipitation statistics rather than precipitation dynamics, we do not present an in-depth dynamical analysis using the large-scale field reconstructions.

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.

These considerations motivate our assessment of the changes in percentiles and percentile changes of standardised regional precipitation data from small domains on the British Isles in observations, 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.

2 Data

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 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, http://climexp.knmi.nl/) 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) 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 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). In the following, we compare the EWP with the two reconstructions over the British Isles.

Our main comparison is to data 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 simulation with the MPI-ESM global climate model in its COSMOS set-up (see below). We use data 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.

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 a T31 resolution 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 the regional model requires to include 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. 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).

The appendix provides a short evaluation of the simulation against the observational CRU-data (Harris et al., 2014) over the European domain.

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 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.

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. In our analyses, we fit a Weibull distribution. Results differ only little if we fit Gamma or Generalised Gamma distributions (not shown). 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 Appendix Figure B1).

For any given sample data, the distribution fit gives among other things information about which precipitation amounts represent especially dry or wet conditions. In the SPI-literature, the 6.7 and 93.3 percentiles represent traditionally the regions of severe (and extreme) dryness/wetness of the probability density function. Accordingly, we subsequently show 6.7 and 93.3 percentiles for the fitted distributions.

Fitting distributions over moving windows allows considering the changing amount of precipitation, which one would consider extremely high or low for subsequent periods, or how likely a reference amount of precipitation is in different periods. We assess how the 6.7 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).

The standardisation procedure provides further means to study the agreement or the lack thereof between different data sources. Agreement in 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 estimated changes may highlight differing internal climate variability between observed/reconstructed and simulated data or it may signal that the simulated data does not correctly capture forced variations.

We concentrate on the period 1700 to 1850 when best estimates of 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).

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 analysis.

4 Results

4.1 Comparison of Temperature data

Figure 1 provides 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 records from 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 the CET data.

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.

The observed Central England Temperature (CET) is the only data whose 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 early 19th 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 PMIP3 simulations seem to show generally less multi-decadal variability but more centennial variability. Some simulations appear to react to the forcing history, others less so. The light colored estimates of a larger domain European temperature suggest a slightly larger forced response.

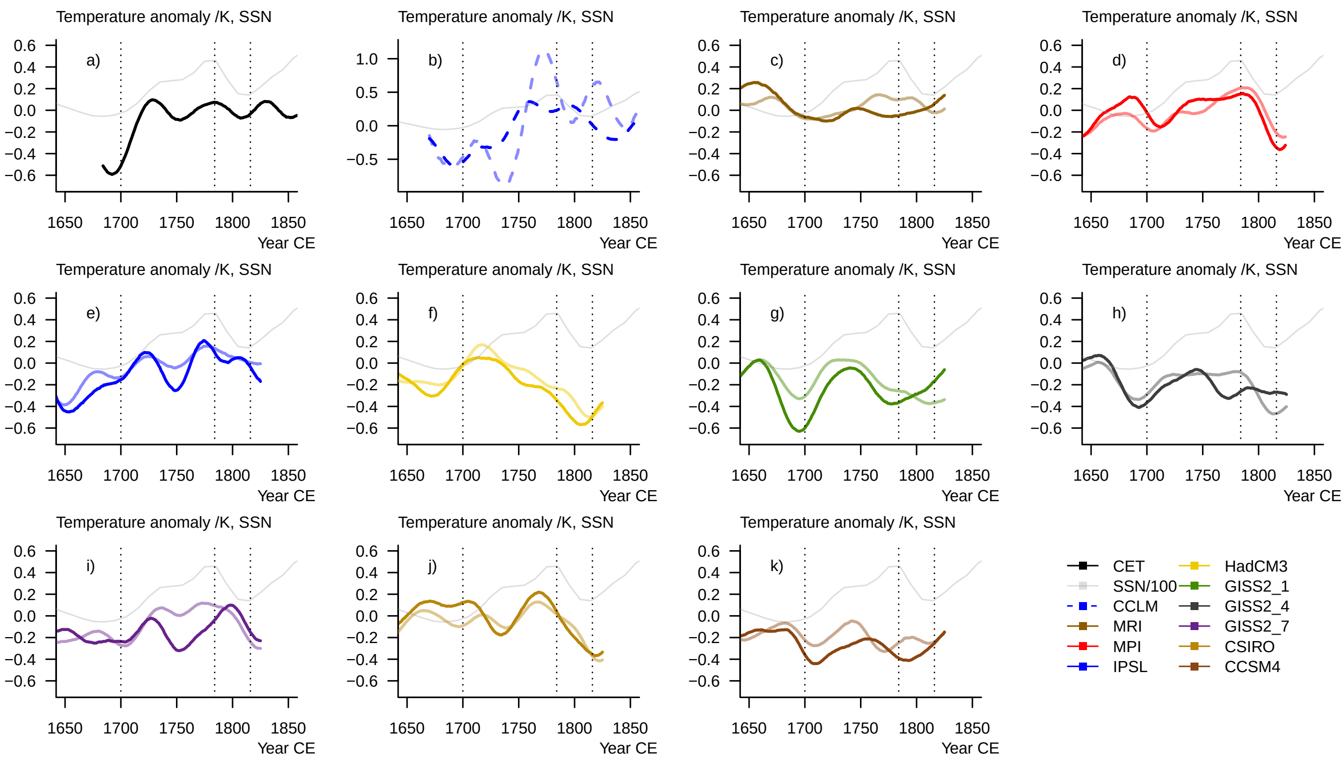

Figure 1. Representations of Central England Temperature smoothed with a 51-point Hamming filter (colored) in various datasets for the period 1650 to 1850 and the Solanki decadal Sunspot Number (light grey in background, divided by 100). Light colors are European domain large-scale mean temperatures. a) observational CET, b) CCLM regional simulation, c) MRI, d) MPI, e) IPSL, f) HadCM3, g) GISS-E2-R 21, h) GISS-E2-R 24, i) GISS-E2-R 27, j) CSIRO, k) CCSM4. Vertical lines give the years 1700, 1784, and 1816.

4.2 Standardised Precipitation

The lacking agreement between the temperature data in Figure 1 reduces our hope of finding agreement in the precipitation data. Figure 2 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 2a) 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, the relative minimum in the early 20th century is more prominent in this data set. The percentiles for severe to extreme dryness (Figure 2g) and wetness (Figure 2d) 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 median.

Differences are generally smaller between both regions for their approximate representations in the regional simulation data (blue lines in Figure 2, left column). The existing differences, however, highlight the spatial heterogeneity of precipitation.

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-27
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Discussion started: 9 May 2018

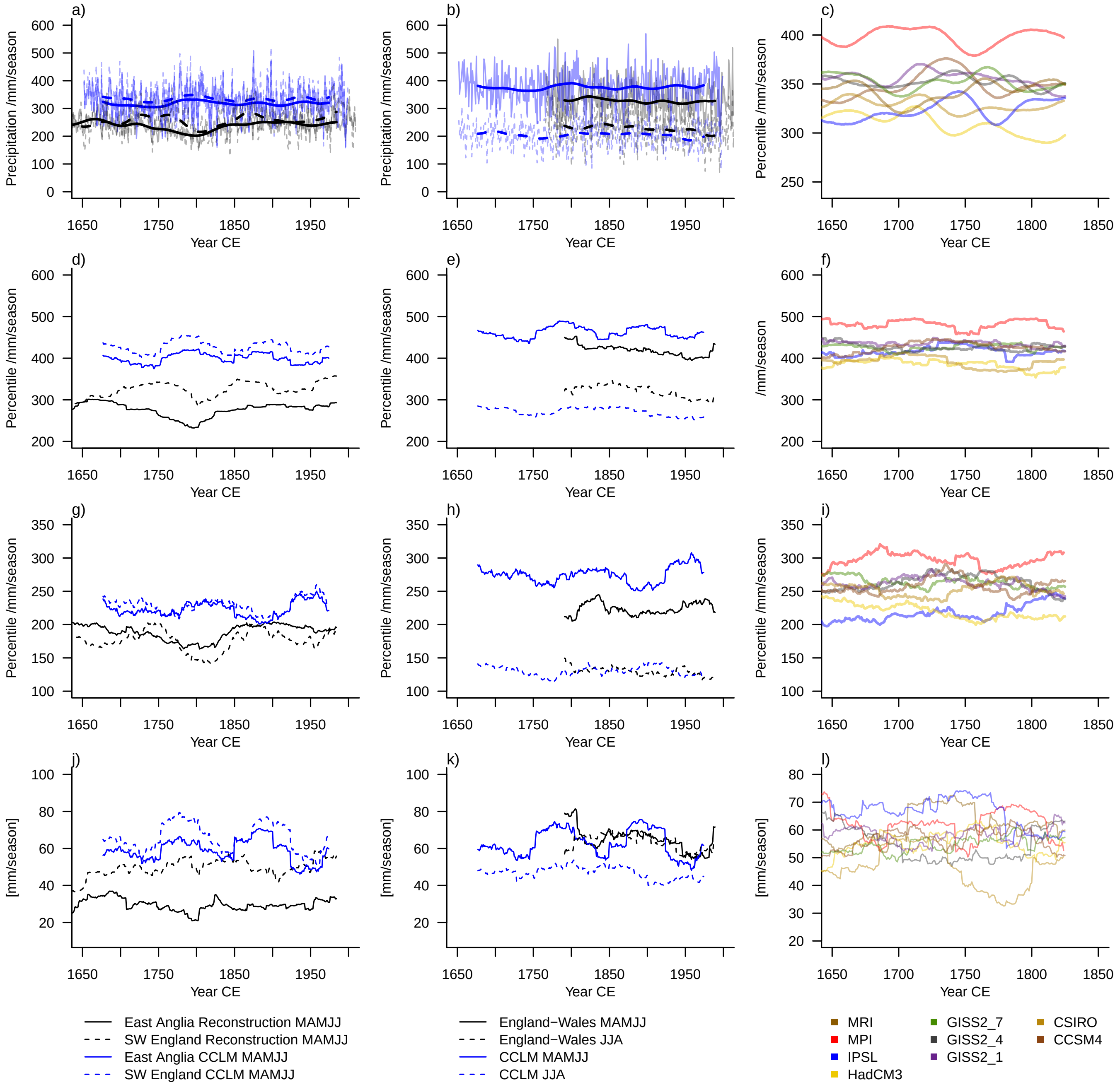

Figure 2. a) East Anglia and Southern-Central England precipitation in reconstructions and regional simulation, annual and 51-point Hamming filtered, b) England-Wales precipitation in observation and regional simulation in MAMJJ and JJA, annual and 51-point Hamming filtered, c) 51-point Hamming filtered 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.

Differences between both simulated data sets become more notable in the percentiles, which may be due to sampling variability (compare Appendix B). Smoothed data and wetness percentiles evolve similarly, but opposite evolutions of the dryness and wetness percentiles results in widening and shrinking of the distributions after about 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 the reconstruction for Southern-Central England in their smoothed evolutions and in the wetness percentile. On the other hand, the dryness percentiles evolve in an opposite way.

If we define a period of interest as between 1650 and 1850, we can generally conclude that the regional simulation and the selected reconstructions for 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 data.

Next, we compare these reconstructions and simulations with the observed England-Wales Precipitation in the months MAMJJ that is available in monthly resolution from the year 1766 onward (Figure 2, central column). 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 2 shows for comparison the representation of 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 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.

Parameters for the fitted distributions allow evaluating the moments of the distributions. The bottom row of Figure 2 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 percentiles represented by a certain given amount of precipitation over time (Figure 3). We analyse changes in the 93.3th, 50th and 6.7th percentiles. The reference for this is the distribution of precipitation in the window centered around the year 1815CE. We estimate and plot the percentiles that correspond to 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 England-Wales MAMJJ precipitation quantiles corresponding to the 50th and 93.3th percentiles in the year 1815. The quantile corresponding to the 6.7th percentile in 1815 appears to become less likely over time (Figure 3, middle column).

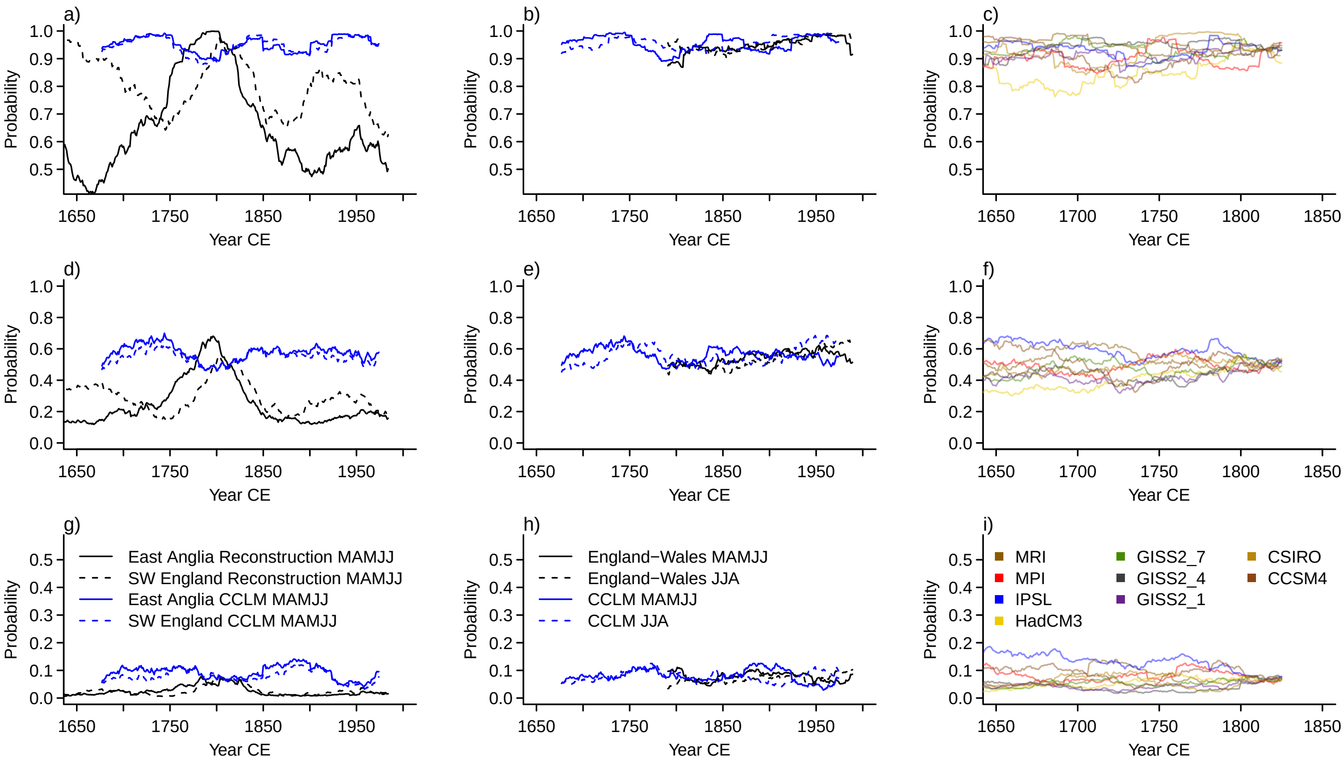

Figure 3. Changes in the cumulative probability over 51-year windows represented by a,b,c) the 93.3 percentile, d,e,f) the 50 percentile and f,g,h) the 6.7 percentiles for the reference year 1815 for a,d,g) East Anglia and Southern-Central England precipitation in reconstructions and regional simulation, 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.

The regional simulation does not show a comparable trend but displays similar overlaid variations though 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.

The reconstructions for East Anglia and South West England have some peculiar features. For one, it is not ideal to choose a reference year from the period around 1800. The 6.7th percentile in 1815 is much less likely previously and later. Similarly, average precipitation around 1815 represents approximately the 20th percentiles in earlier and later periods. Severe and extreme wet conditions from this period may even represent long-term average conditions for East Anglia.

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.

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-27
Manuscript under review for journal Clim. Past
Discussion started: 9 May 2018

Climate of the Past Discussions

4.3 Relation between Temperature and Precipitation

We pointed above at how the temporal evolutions of regional temperature differed between the different data sets and then presented the differences in precipitation variations between the simulations, the reconstructions, 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.

Figure 4 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 4e-h). We emphasize the MPI-ESM and GISS24 simulations in Figure 4. 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.

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 sets. 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 Southern-Central England, the positive relation fails in the most recent part of the records.

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.

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 temperature signal, for instance, if they are sensitive to soil moisture.

Since correlations between the running measures over moving windows capture only the very low frequent variability in these moving windows, Figure 5 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 -0.59

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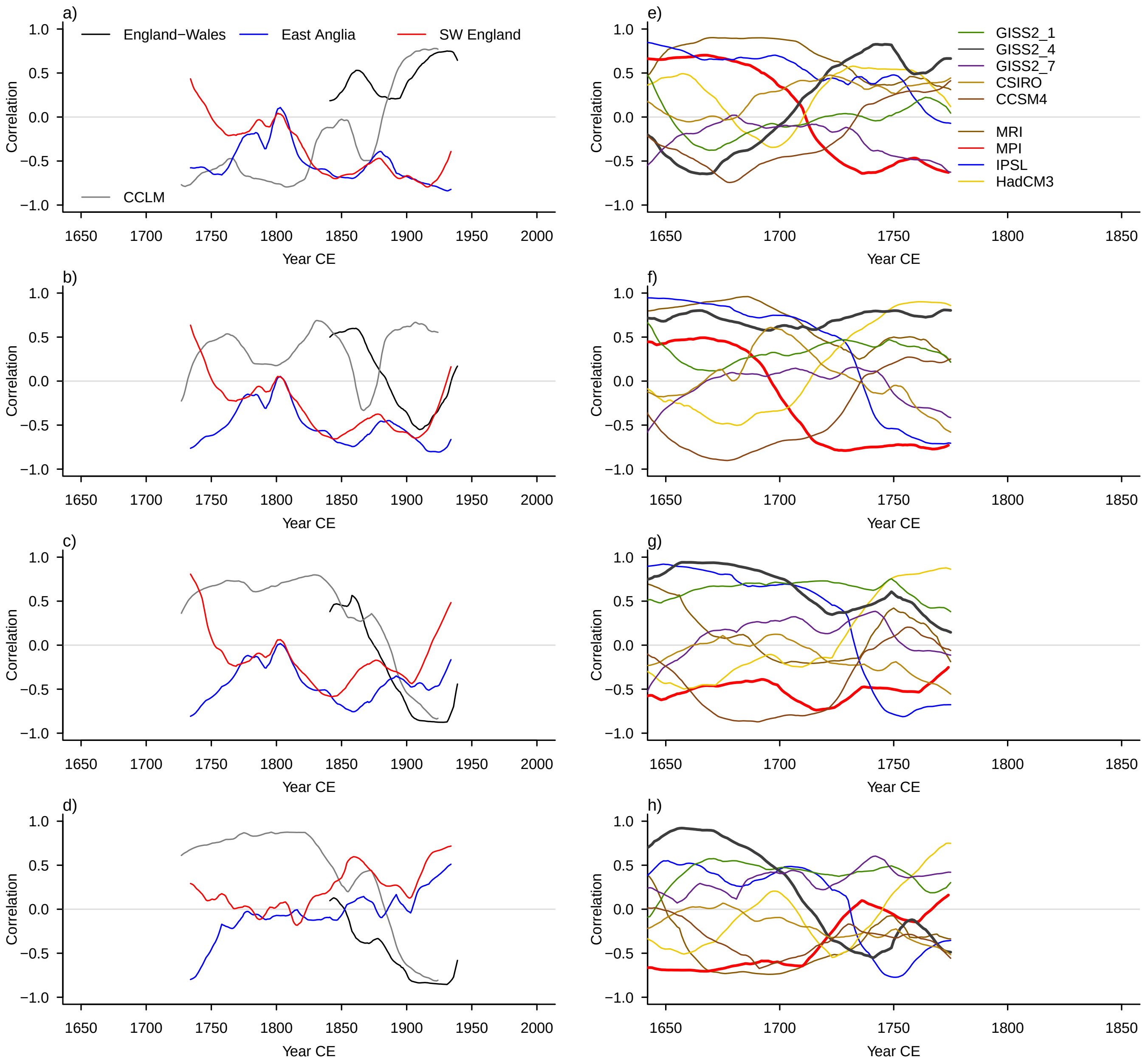

Figure 4. Correlations between Central England temperature and precipitation distribution measures over 101-year windows, a,b,c,d) Reconstructions, observational data, and regional simulation, e,f,g,h) the PMIP3 ensemble England-Wales precipitation; a,e) 6.7 percentile, b,f) 50 percentile, c,g) 93.3 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.

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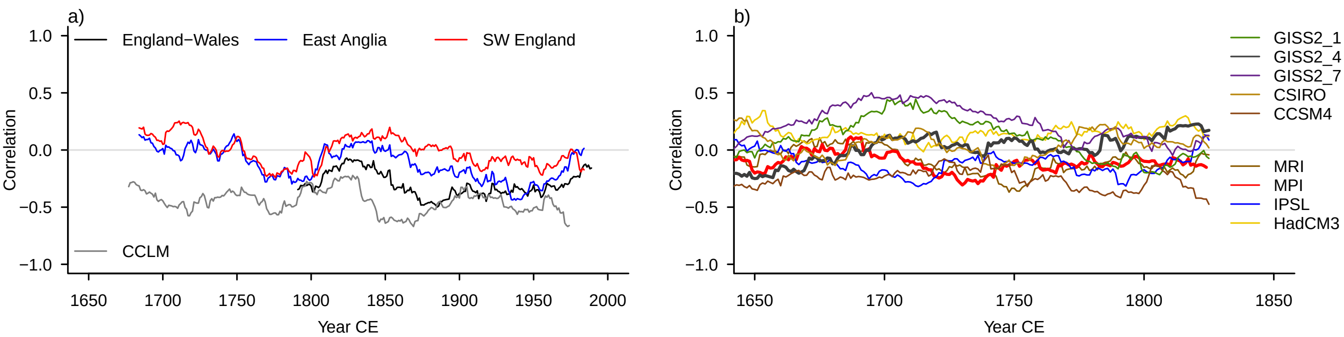

Figure 5. Interannual correlations over gliding 51-year windows between Central England temperature and precipitation data sets, a) Reconstructions, observational data, and regional simulation, b) the PMIP3 ensemble England-Wales precipitation. Note the different ranges of the x-axes between the PMIP3-simulations 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.

and about -0.21 for a correlation of about -0.43 between simulated CET and EWP over the full period. That is, variations in Figure 5 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 correlations. We do not show significance levels in Figure 5. We note that for 51-year windows and the 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.

On interannual timescales and over 51-year moving windows, all data sets evolve similarly in Figure 5a. However, recently the regional simulation behaves opposite to the reconstructions and the observations. Both reconstructions do not show any relation between temperature and precipitation. 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.

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 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 that regional climate simulations usually capture this feature successfully.

Figures 4 and 5 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.

Furthermore the agreement between different data sources about the relation between temperature and precipitation is apparently time-scale dependent for the short data series we use, according to Figures 4 and 5. For decadal data, observations, a reconstruction, and the regional simulation appear to represent comparable evolutions. Whether this is a dynamical feature or an imprint of the forcing data remains unclear.

5 Discussion

Figure 1 gave slight indications of a positive relation between natural external climate forcings and the Central England Temperature (CET) and of the absence of this link in simulations. As Frank et al. (2007) noted early instrumental temperature observations are not without caveats. Additionally, the very early data in the CET 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 are wrong but may simply suggest that internal natural climate variability dominates, e.g., the atmospheric circulation masks, modulates, or counteracts an external forcing influence.

In turn, we do not necessarily expect the PMIP3 simulations 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, e.g., the North Atlantic Oscillation, is large (Gómez-Navarro et al., 2012; Gómez-Navarro and Zorita, 2013). 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., 2012). 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.

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 the PMIP3 ensemble.

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 the data. 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 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 compared to the observations, it is unclear whether it does so for the right reasons.

We expect disagreement between simulations and observations on some levels. More critical appears 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 3). 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 recently. Even though reconstructions and observations represent different regional domains, we tend to the inference that the disagreement between the observations and reconstructions suggest major shortcomings in the reconstructions, if we view the observations as the more reliable data set.

Both Wilson et al. (2013) and Cooper et al. (2013) already discuss the possibility that the tree-species used for their reconstructions were less sensitive to precipitation over certain periods, 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.

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 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 climate model simulations for the last 350 years. We chose a small regional domain over the British

Isles 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.

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 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 limited agreement with its observational target but less so with the reconstructions. However, 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 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.

Another important result is the at times opposite evolution of the reconstructions and the regional simulations in regional dryness and wetness. However, we are not able to attribute it to the external forcing or to errors in either data source. Furthermore, 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.

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 temporal scales (Deser et al., 2012). However, the differing 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.

Data availability. Simulation data for the PMIP3-past1000 simulations is available from the nodes of the Earth System Grid Federation, e.g., https://esgf-node.llnl.gov/projects/esgf-llnl/.

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/.

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 Figshare.

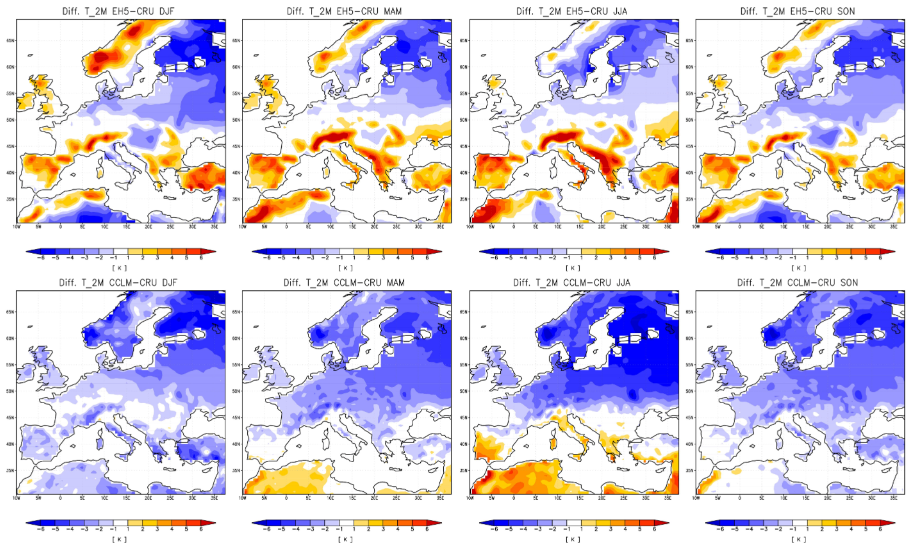

Figure A1. Top: Difference between the driving MPI-ESM simulation and the CRU data for seasonal near surface air temperature. Bottom: Difference for CCLM

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).

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. It is generally too cold over the Baltic region, the eastern part of the model domain, the 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 of the domain in spring and summer. Cold biases are common otherwise and are largest over the Northeast frequently exceeding 3-4K.

Considering 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.

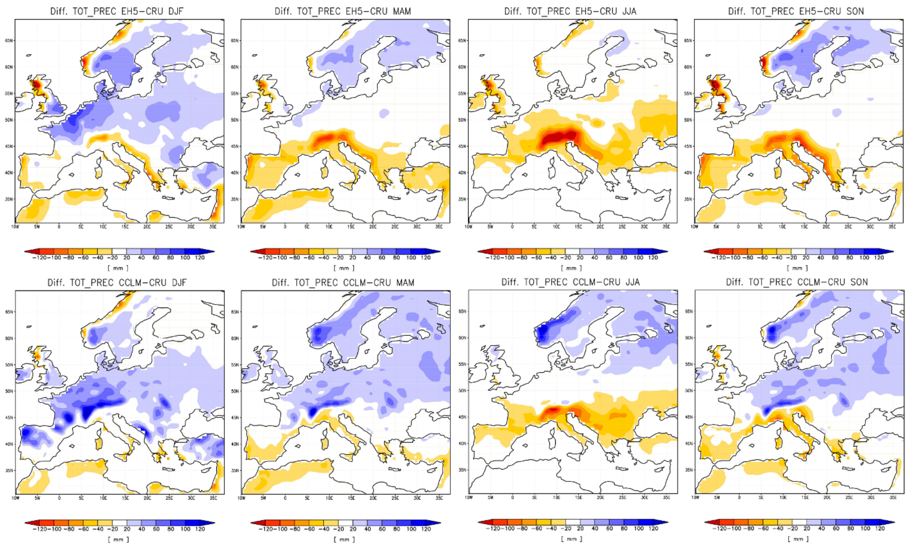

Figure A2. As Figure A1 but for the precipitation

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.

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 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.

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.

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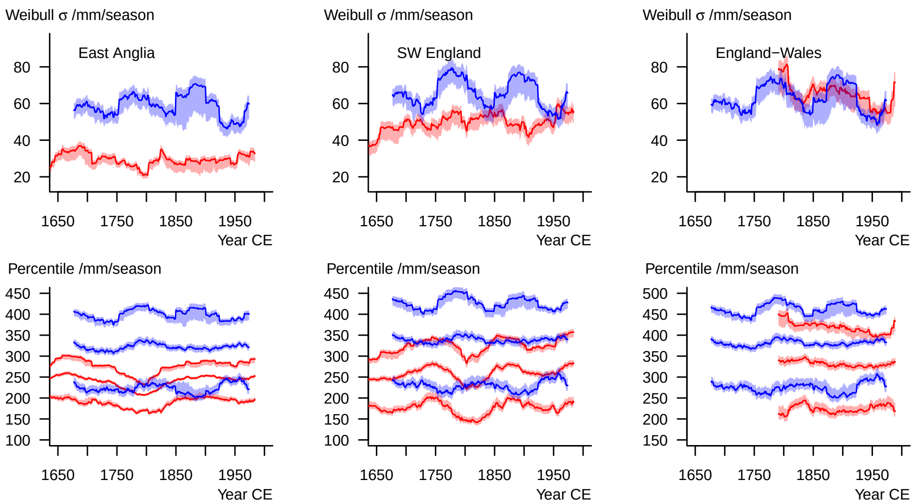

Figure B1. Visualisations of uncertainty on running estimates with 1000 resamplings of 40 samples from each window; units are precipitation amounts. Shading are 95% intervals, lines are medians. Top row: Weibull standard deviation. Bottom row: percentiles. Red: Reconstruction and observations. Blue: CCLM.

Appendix C: 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, 2017) packages helped in the work: gtools (Warnes et al., 2015), ncdf (Pierce, 2015), VGAM (Yee, 2015), MASS (Venables and Ripley, 2002), nortest (Gross and Ligges, 2015), dplR (Bunn et al., 2017), zoo (Zeileis and Grothendieck, 2005), latex2exp (Meschiari, 2015), knitr (Xie, 2015), and rmarkdown (Allaire et al., 2017). Furthermore, RStudio (RStudio Team, 2016) was essential.

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 do not declare any competing interests.

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and Wilson et al. (2013). We acknowledge the SPI-code provided by Frank Sienz (e.g., Sienz et al., 2012). Christian Zang provided input for a computationally efficient Gershunov-test.

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