https://doi.org/10.5194/cp-2019-81
Preprint. Discussion started: 5 July 2019

Climate of the Past Discussions

Proxy surrogate reconstructions for Europe and the estimation of their uncertainties

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Abstract. Combining proxy information and climate model simulations allows reconciling both sources of information about past climates. This, in turn, strengthens our understanding of past climatic changes. The analogue or proxy surrogate reconstruction method is a computationally cheap data assimilation approach to benefit from the advantages of both data sources. We use the approach to reconstruct European summer mean temperature from the 13th century until present using the Euro 2k set of proxy-records and a pool of global climate simulation output fields. Previous applications of the analogue method to combine proxy records and simulations did not provide uncertainty ranges. Here, we provide several ways of estimating reconstruction uncertainty for the analogue method, which take into account the non-climate part of the variability in each proxy record.

In general, our reconstruction agrees with the Euro 2k reconstruction, which had been conducted with two different statistical methods and using no information from model simulations. At interannual timescales, differences between our reconstruction and the Euro 2k reconstructions may be large, but they are much smaller at multi-decadal timescales. In both methodological approaches, the decades around year 1600 CE were the coldest. The approaches do not agree, however, on the warmest preindustrial decades, which the Euro 2k reconstruction places in the early 15th century and the analogue approach in the early 18th century.

The surrogate reconstructions also represent the local variations of the observed proxies even under uncertainty but local uncertainties of the temperature reconstructions tend to be large in areas that are poorly covered by the proxy records. Uncertainties highlight the ambiguity of field based reconstructions constrained by a limited set of proxies.

1 Introduction

There have been numerous efforts to reconstruct regional to global surface temperature for the last 500 to 2000 years. Many of the statistical reconstruction methods essentially assume a linear relationship between the paleo-observations from proxies and temperature data. Here we apply a non-linear method, the analogue method, to reconstuct the mean European summer temperature over the past 750 years. Our approach relies on a collection of dendroclimatological records and the output of paleoclimate simulations. Our main goal is to provide a perspective on estimating uncertainties for reconstructions by analogue because most previous analogue reconstructions do not provide such estimates.

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The core of the analogue method is the search for similar spatial patterns in simulated temperature data compared to the paleo-observations. That is, we search for simulated analogues of the climate anomalies indicated by the set of proxies at each time step. Similar approaches originated during the Second World War when the US Air Force catalogued weather situations of previous decades as a means of long range weather forecasting. In this approach forecasters obtain forecasts by analogy between current observations and a past set of weather patterns (Namias, 1948). Lorenz (1969) was the first to mention the method in the wider academic literature.

The analogue method found subsequent applications not only in downscaling of climate information (e.g., Zorita and von Storch, 1999). In the paleoclimate-context, Graham et al. (2007) rename the method into Proxy Surrogate Reconstruction method and use the analogy between proxy-observations and simulated climate states. Subsequently a number of authors use the approach for climate index and climate field reconstructions of past climate states (e.g., Franke et al., 2010; Trouet et al., 2009; Gómez-Navarro et al., 2014; Gómez-Navarro et al., 2017; Jensen et al., 2018; Talento et al., 2019). Modern analogue techniques of varying complexity are also common in paleoecology (e.g., Graumlich, 1993; Jackson and Williams, 2004).

Our understanding of past climate changes depends on the consilience of our different avenues of evidence like simulations and reconstructions. The analogue method is a computationally cheap means to contrast information from both simulations and reconstructions in the sense of data assimilation though methodologically less sophisticated. The method allows to reconcile the spatially sparse information from environmental and documentary proxy data with spatially complete and dynamically consistent though possibly biased information from observational data or long climate simulations (Graham et al., 2007; Trouet et al., 2009; Guiot et al., 2010; Franke et al., 2010; Luterbacher et al., 2010; Schenk and Zorita, 2012; Gómez-Navarro et al., 2014; Gómez-Navarro et al., 2017; Jensen et al., 2018; Talento et al., 2019). This can provide a dynamic understanding of past climate variability in terms of a guesstimate. Gómez-Navarro et al. (2017) provide a short comparison with more complex data assimilation-techniques. Annan and Hargreaves (2012) test a particle-filter method in a perfect model setting and find a trade-off between accuracy and reliability of reconstructions dependent on quality and quantity of the available proxy-records. Since simple analogue search approaches and particle filter methods share common assumptions, this trade-off also applies for analogue search reconstructions.

Franke et al. (2010) show the very good agreement of their proxy surrogate reconstruction in terms of the area averaged indices and also at the locations of instrumental data used as predictors. However, reducing the number of predictors prominently worsens the skill at remote locations. Gómez-Navarro et al. (2014) show further evidence for the accumulation of skill at the predictor locations (see also Annan and Hargreaves, 2012). Franke et al. (2010), Gómez-Navarro et al. (2014), and Talento et al. (2019) discuss the influence of considering more than one analogue to produce a composite reconstruction while Graham et al. (2007) and Trouet et al. (2009) consider only the single best analogue based on specific criteria.

These approaches usually assume that there is no uncertainty in the predictor data and do not provide an uncertainty estimate for the final reconstruction. This does not provide a realistic evaluation of predictors or reconstruction. An exception is the study by Jensen et al. (2018), which uses age-uncertain proxies and obtains an uncertainty estimate of their reconstruction through shifting the dates of individual proxies.

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Here we propose that we can provide a reconstruction uncertainty based on the calibration correlation of the proxy predictor with an appropriate observational data set. While the estimation of those uncertainty ranges reduces the possibility of producing time series of reconstructed climate, it allows providing alternative reconstructions that are compatible with the sparse information provided by the proxy records. The procedure further acknowledges the possibility that the analogue pool does not cover certain points in the predictor space.

Recent continental proxy-based reconstructions (PAGES 2k Consortium, 2013) and the underlying proxy predictors are potential test cases and allow to assess the analogue method against more common reconstruction procedures. (Dis)agreement between the analogue reconstructions and previously published estimates helps to reevaluate our confidence in our understanding of past climate changes. For the present purpose, we choose the European reconstruction from PAGES 2k Consortium (2013) as a single test case. See also the work by Luterbacher et al. (2016), who discuss the methods and the proxy-selection in more detail. Luterbacher et al. (2016) rigorously select proxy records of high quality for their reconstruction.

2 Methods & Data

2.1 Methods

2.1.1 Analogue Search Reconstructions

The paradigm that past analogues may provide information for anthropogenic climate changes is pervasive in climate science (Dahl-Jensen et al., 2015; Schmidt, 2010; Schmidt et al., 2014) but the origin of the analogue method lies in weather forecasting (see, e.g., Lorenz, 1969). Zorita and von Storch (1999) show the method's value for downscaling while others provide evidence for its ability to upscale local information (e.g., Schenk and Zorita, 2012; Luterbacher et al., 2010; Franke et al., 2010).

Here, we obtain large-scale fields of summer temperature based on a pool of relevant candidate fields and a set of local data indices as predictors for the period 1260 to 2003 of the Common Era (CE). The reconstruction domain is -10E to 40E and 35N to 70N (Figure 1). The approach is that, for each set of predictors, i.e. each point in time, one ranks all potential analogues according to a criterion of similarity to the target proxy pattern. This criterion is traditionally the Euclidean distance and only the single pool-member with the smallest Euclidean (e.g., Franke et al., 2010) or a low number of so defined best analogues is considered.

The approach presented here differs from previous applications in some important aspects. While we also show a single best-analogue reconstruction and a reconstruction based on a fixed number of analogues, we add a reconstruction that explicitly considers the uncertainty of the proxy records in the selection of the analogue fields. The next subsection provides details.

We consider predictors and analogues normalized by their local standard deviation to conserve the interfield relations. The final reconstructions are rescaled by a chosen standard deviation, which is, here, usually the local full period standard deviation of one of the simulations.

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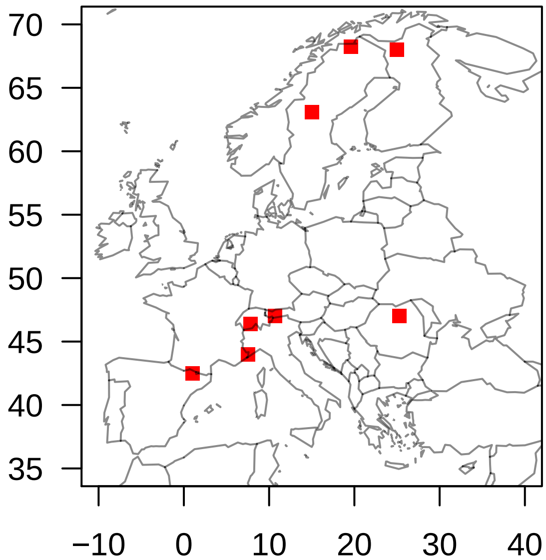

Figure 1. Reconstruction domain and locations of the included proxies.

2.1.2 Assumptions on uncertainty

Empirical reconstructions of past environmental conditions generally use measurements on archives. That is, they use recent observations, which measured archives, which in turn recorded the past environmental conditions (see, Evans et al., 2013). The observations may be documentary notations but more often are measurements of biological, geological, or chemical properties of the archives. Such proxy representations of the past conditions are naturally uncertain. The most obvious source of uncertainty is the sensitivity of the archives (e.g., trees) to more than one environmental condition (e.g., Evans et al., 2013; Tolwinski-Ward et al., 2013; Evans et al., 2014; Tolwinski-Ward et al., 2015).

Correlations provide a simple measure of the relation between proxy-observations and an environmental condition over a period when reliable (instrumental) observations of the environmental condition exist. From the correlation coefficients, and under certain simplifying assumptions, we can derive the uncertainty in representing the local climate by the local proxy record as described in the following. We denote this uncertainty hereafter as proxy uncertainty.

Assuming one can interpret the squared correlation coefficient (R^2) as explained variance, one can profit from the equivalence $R^2 = 1 - MSE_{res}/MSE_{tot} = 1 - Var_{res}/Var_{tot}$ if we take the considered mean squared errors (MSE) as unbiased. The subscripts are *res* for residual and *tot* for total.

We can take the total variance Var_{tot} to be equal to the variance of the sum of a signal (subscript *sig*) and the residual noise. If we assume these are uncorrelated, we obtain $1 - R^2 = Var_{noi}/(Var_{sig} + Var_{noi})$. We replaced the residual variance by the noise variance (subscript *noi*) and reorganised the equation.

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If we consider normalized data, the total variance becomes one, $Var_{tot} = 1$. For a simulated climate record in a grid-cell of a climate model, there is no uncertainty and, then, it is indeed $Var_{tot} = Var_{sig} = 1$, i.e. the total variance is pure signal. For the case of a normalized proxy we take $Var_{tot} = 1 = Var_{sig} + Var_{noi}$ and thus $1 - R^2 = Var_{noi}$.

In our present approach, we consider normalized proxy data, i.e., $Var_i = 1$ for an individual proxy i. We also consider normalized simulated records, i.e. $Var_{sim} = 1$. Our goal is to replace a simple criterion of similarty between proxy patterns and simulated (analogue) patterns with a new criterion that also takes into account the inherent uncertainty in the proxy records. Candidate analogues then may provide a credible envelope on the analogue reconstruction dependent on the available data. With simulated unit variance, the noise standard deviation becomes $SD_{noi} = \sqrt{1 - R^2}$. Based on these assumptions, there are a number of possible approaches to obtain uncertainties of a reconstruction by analogue.

One possibility to define this modfied similarity criterion is to assume that the noise standard deviation represents a noise tolerance value for every proxy included in our analogue search. We then can limit our analogue search to only those analogues within a certain tolerance range at each location, i.e. within plus and minus one, two, or three SD_{noi} around the proxy value.

Alternatively, we can use the individual values for all proxies to construct a maximally tolerated Euclidean distance. The obvious caveat of this latter approach is that the analogues may locally lie outside the tolerance range of some of the proxy records although the Euclidean distance is smaller than the maximally tolerated value. On the other hand, the criterion that the analogue should lie within each individual proxy tolerance may exclude the overall best analogue according to the minimal Euclidean distance. We consider this downside acceptable.

Generally, there may be at best a few locally tolerable analogues for a certain date according to a defined tolerance criterion. We find for our application that a one SD_{noi} tolerance provides no tolerable analogue for 35 dates. Similarly $1.64\,SD_{noi}$ and $1.96\,SD_{noi}$ criteria still imply that we find less than ten analogues for one year (2003).

Obviously, the real benefit of the proposed method is to use only analogues, which comply with a certain tolerance criterion. In the following, we choose a tolerance criterion of $2.57\,SD_{noi}$ to provide a reconstruction at each date for the full period. We restrict the number of analogues for all dates to a constant number, which is the smallest number of available analogues at any date within the full period. If we include the year 2003, the minimal number of analogues is 39. It increases to 156 excluding the year 2003.

However, the one-standard deviation criterion is the only one that gives a subjectively reasonable maximal number of 2105 possible analogues. Thus, subsequently, we also discuss results for a fixed one SD_{noi} interval. Both sets of results are also compared to a single best-analogue reconstruction.

Our time-series plots present a number of uncertainty envelopes. The first one is motivated by the considerations detailed above. If we show normalized series, we assume that the square root of the sum over the individual proxy noise variances (Var_{noi_i}) divided by the number of proxies represent one standard deviation uncertainties. However, for plotting temperature series, we have to rescale these estimates. We do this simply by multiplying the noise variances in the square root by a selected grid-point variance.

Additionally, for ensembles of analogues, the full range of the ensemble is plotted, and another envelope bases on the intra-ensemble variance. Finally, for single best-analogue reconstructions, a credible envelope is given by the MSE between the

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Table 1. Proxies considered, their geographic position, and their correlation to the observations over the period 1901 to 2003. The data is from PAGES 2k Consortium (2013).

Proxy & ID	Lon	Lat	Correlation
Torneträsk, Sweden, Tor92	19.6 E	68.25 N	0.79
Jämtland, Sweden, Jae11	15 E	63.1 N	0.65
Northern Scandinavia, Nsc12	25 E	68 N	0.74
greater Tatra region, Slovakia, Tat12	20 E	49 N	0.16
Carpathian, Romania, Car09	25.3 E	47 N	0.56
Alps, Austria, Aus11	10.7 E	47 N	0.75
Alps, Switzerland, Swi06	7.8 E	46.4 N	0.68
Alps, France, Fra12	7.5 E	44 N	0.52
Pyrenees, Spain, Pyr12	1 E	42.5 N	0.41
Albania, Alb12	20 E	41 N	-0.16

normalized proxy-values and the normalized best-analogue values at the closest grid-point. We generally show 50% intervals and rescale uncertainties to represent temperatures.

2.2 Data

2.2.1 Proxies

The target of our application of the analogue method is a representation of European temperature in summer, June, July, August (JJA), equivalent to the original Euro 2k-reconstruction by the PAGES 2k Consortium (2013). Therefore, we rely on the proxy-selection of the Euro-Med 2k Consortium (see also Luterbacher et al., 2016), for individual references see PAGES 2k Consortium (2013) and Luterbacher et al. (2016). Since neither the Albanian nor the Slovakian proxy records provided by the PAGES 2k Consortium (2013) explain a relevant portion of the CRU-TS-3.10 (Harris et al., 2014) summer temperature data at the closest grid-point, we exclude them from the following reconstruction efforts. Table 1 gives the correlation between the proxy series and the CRU-data over the period 1901 to 2003. Figure 1 shows the proxy locations.

Furthermore, since the Dobrovolný et al. (2010) Central European data is a spatial average, we also do not consider it in the reconstruction. All three excluded records, however, are subsequently compared to the reconstructed local series. Although two of the Euro 2k proxy series extend back to the year 138 BC, we only describe results for the period 1260 to 2003. The last of the remaining eight proxy indices starts in 1260.

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Table 2. Simulations in our pool of analogue candidates: ID, forcing components, data reference. Forcings are stratospheric sulphate aerosols from volcanic eruptions (V), variations of total solar irradiance (large amplitude: S, small amplitude: s), changes in earth's orbit (O), land use change (L), greenhouse gases (G); note, only methane and nitrous oxide were prescribed, the carbon dioxide concentration was calculated interactively. For details see data references and Jungclaus et al. (2010).

ID	Forcing	Reference
mil0010	VsOLG	Jungclaus (2008a)
mil0012	VsOLG	Jungclaus (2008b)
mil0013	VsOLG	Jungclaus (2008c)
mil0014	VsOLG	Jungclaus (2008d)
mil0015	VsOLG	Jungclaus (2008e)
mil0021	VSOLG	Jungclaus and Esch (2009)
mil0025	VSOLG	Jungclaus (2009a)
mil0026	VSOLG	Jungclaus (2009b)

2.2.2 Model simulations

Thanks to the PMIP3-effort (Paleoclimate Modelling Intercomparison Project phase 3, e.g., Schmidt et al., 2012) there is a strong ensemble of simulations for the last 1100 years, with a number of additional simulations compliant with the PMIP3 protocol but not included in the effort (Jungclaus et al., 2010; Fernández-Donado et al., 2013; Lohmann et al., 2015; Otto-Bliesner et al., 2016). Wagner (personal communication, 2016, 2019) has performed a simulation for the last 2,000 years, and Gómez-Navarro et al. (2013, see also Gómez-Navarro et al., 2015) and Wagner (personal communication, 2014, 2018, 2019, see also Bierstedt et al., 2016, Bothe et al., 2019) have performed regional simulations for Europe for approximately the last 500 years. All these simulations would be suitable as pool of analogues. Especially the PMIP3-ensemble is easily available.

We opt here for a single model ensemble predating the PMIP3-effort but compliant with its protocol, i.e. the millennium simulations with the COSMOS-setup of the Max-Planck-Institute Earth System Model (MPI-ESM) by Jungclaus et al. (2010). This choice bases not least on the assumption that the simulations provide a very similar internal variability to rescale the normalized data (see section above). Furthermore, one may assume that the single model ensemble provides data with a consistent bias throughout the ensemble. Obviously, the shortcomings in simulating ENSO (Jungclaus et al., 2006) are prominent in the MPI-ESM-COSMOS ensemble and affect the results. Since the current manuscript is not least a proof of concept, this is an acceptable caveat to the results. We use data centered on the full period 1260 to 2003 and the data is normalized with the standard deviation over the same period. Jungclaus et al. (2010) provide details on the simulations (see also data references in Table 2). We use simulation output from the ensemble members including all forcing components for the period 800 to 2005 CE (Table 2). Forcings are solar, volcanic, greenhouse gas, orbital, and land use; the carbon dioxide concentration was calculated interactively (compare Jungclaus et al., 2010).

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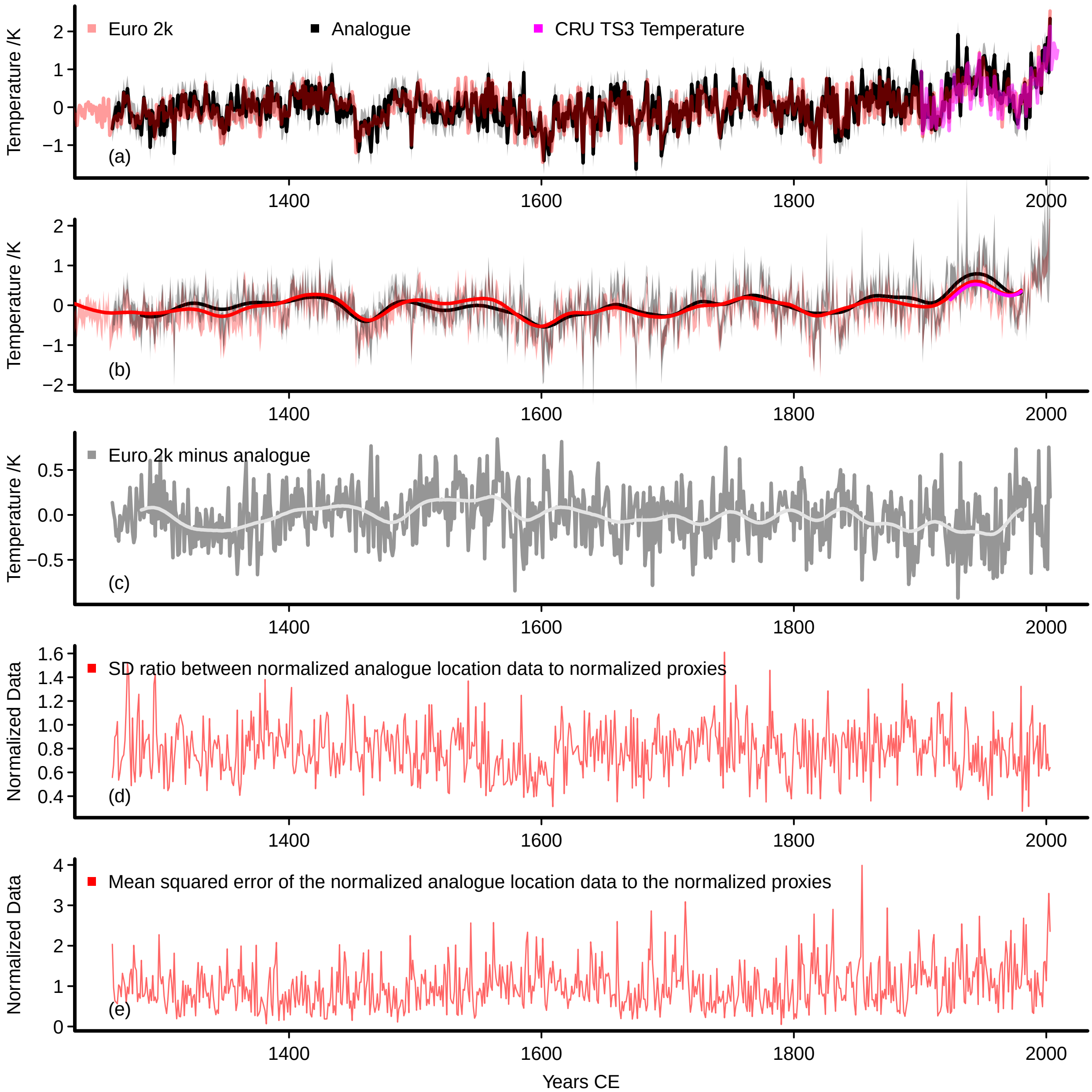

Figure 2. Summary of the best-analogue reconstruction: **(a)** the interannual rescaled temperature reconstruction in black and an 50% uncertainty in grey based on the correlation between the the proxies and the observations at the proxy locations; the red line is the Euro 2k-reconstruction; magenta is the observational CRU temperature adjusted to the mean of the reconstruction over its time-range. **(b)**: as (a) but for 47-point Hamming filtered data; red shading is the unsmoothed Euro 2k-uncertainty; the narrower additional grey envelope is a 50% uncertainty based on an MSE-estimate. **(c)**: Difference between the Euro 2k and the analogue reconstruction and its smooth. **(d)**: Ratio between the standard deviations of the analogue values at the closest grid-points to the proxy values. **(e)**: Mean squared error between analogue grid-point values and the proxies.

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3 Results

3.1 Single best-analogue reconstruction

Figure 2 summarises the single best-analogue reconstruction. There is generally very good agreement between the Euro 2k and the analogue reconstruction but the latter appears to overestimate the warming since the early 19th century. Note that the observational data is plotted relative to the mean of the Euro 2k-reconstruction over the observational period and solely provides a qualitative comparison.

The analogue reconstruction shows rather small centennial variations as does the Euro 2k-reconstruction. We note that the Bayesian Hierarchichal Modelling (BHM) reconstruction by Luterbacher et al. (2016) shows larger variations compared to their composite-plus-scaling reconstruction in the early part of the last millennium prior to our study period. The larger warming since about 1800 in the analogue reconstruction is in line with a slightly larger warming in the BHM-reconstruction by Luterbacher et al. (2016).

The difference plot in Figure 2c shows the size of the interannual differences between the Euro 2k composite-plus-scaling reconstruction and the best-analogue reconstruction. These differences do not exceed 1 degree Kelvin. Smoothed differences emphasize that there is structure in the differences with periods of over- and underestimation. Differences are especially large in periods before the 1600s and since about 1800.

Figure 2b shows the smoothed records plus unsmoothed 50% uncertainty intervals for the two reconstructions, where the Euro 2k uncertainty intervals are derived from the data provided by the PAGES 2k Consortium (2013). The Euro 2k uncertainty intervals base on the range of a nested composite-plus-scale reconstruction ensemble and the standard-deviation of the reconstruction-validation residuals (see supplement to PAGES 2k Consortium, 2013).

The uncertainty intervals for the analogue reconstruction are calculated as the square root of the sum over the Var_{noi} for the invdidual proxies divided by the number of proxies. We assume these represent one standard deviation uncertainties. However, they are only an approximation of the uncertainty. From these we calculate the assumed 50% intervals. The second, generally narrower uncertainty envelope in Figure 2b bases on the mean squared errors between the proxy-values and the best-analogue values at each date.

The noise variance based envelope also is notably narrower than the uncertainty of the Euro 2k-reconstruction although this is hard to identify in Figure 2b. Neither the Euro 2k nor the best-analogue reconstruction generally fall outside of an assumed 95% interval of the other reconstruction. While the noise-based envelope is a constant measure of the uncertainty, the mean-square-error envelope evolves over time. Its width is sometimes closer to the Euro 2k uncertainty and sometimes closer to the square root of the sum over the noise variances for the proxies. It occasionally becomes very wide highlighting years when the analogues are bad fits for the proxies, e.g., the years 2001 and 2003 CE.

Next we shortly describe some features of interest over the period 1260 to 2003 CE. We only consider the best-analogue reconstruction estimate without the associated uncertainties. The coldest century was until 1648 CE in the best-analogue reconstruction but until 1678 CE in the Euro 2k record. Although the start date in 1260 CE prevents an assessment of the Medieval Climate Anomaly, it is interesting that these two reconstructions both have the warmest century from 1353 until

1452 CE for the period until 1850. Considering the full period until 2003, the last hundred years were warmest. The coldest 30-year period ends in 1608 CE in the analogue reconstruction and in 1616 CE in the Euro 2k data. Warmest 30-year periods end in 1435 and 1781 CE respectively for the data until 1850. Both records disagree on the warmest 30-year period in the 20th century. While the analogue reconstruction is warmer mid-century, the Euro 2k data has the warmest climatological period ending in 2003 CE. The coldest decade occurs in the best-analogue reconstruction and in the Euro 2k-reconstruction between 1600 and 1609 CE. The warmest decade occurs in the early 15th century for the Euro 2k data but ends in 1782 for the best-analogue reconstruction if we only consider the data until 1850. Considering the full period until 2003, the last decade of the data was the warmest decade in both reconstructions. Note again, this description ignores the uncertainties of the records.

We now consider the response to volcanic forcing, as volcanoes are considered to be the most important external forcing over the pre-industrial period. They are also the best constrained past climate forcing for the last 500 to 2000 years (e.g., Sigl et al., 2015; Wilson et al., 2016). The period of our reconstructions includes only a few of the large tropical eruptions of the last millennium. If we consider a subselection of events in 1286, 1345, 1458, 1601, 1641, 1695, 1809, and 1815, a superposed epoch analysis shows usually some cooling though it may be quite small (not shown). Noteworthy is the lack of a clear response for , e.g., the Kuwae eruption, which took place in 1458 CE according to Sigl et al. (2015). The lack of a response in the reconstruction indeed mainly reflects the lack of a clear signature of this event in the proxies entering the reconstruction (not shown). Considering fields for some of these events, superposed epoch analyses may show summer cooling, but, e.g., the year 1459 shows widespread slightly warmer conditions.

Figure 3 plots both the proxy-values as squares and the best-analogue values at the closest grid-points as lines for years of interest and arbitrarily selected years. Proxies excluded from the reconstruction are grey and proxies included are red. It is encouraging to see how close the analogue agrees with the proxies, e.g., for the year 1827. Nevertheless, notable differences occur as well, e.g., for the years 1601 or 2002. Interestingly, the analogues even appear to occasionally capture the relation between the proxies included and those excluded. This small selection of cases indicates that the considered simulation ensemble does quite well represent the relation between the considered regions. A slightly disconcerting feature is visible for, e.g., the year 1947. Then the analogue appears to underestimate the intra-location variability. This is highlighted by Figure 2d which shows the relation between the standard deviation of the best-analogue locations and the standard deviation of the proxy records over time. While the intra-grid-point variability can be larger than the intra-proxy variation, it is apparent that the quotient is more often smaller than one indicating that the intra-proxy variation is larger. The bottom panel of Figure 2 plots the mean squared error of the best-analogue locations and the proxy values. The errors often are rather small, but there are times when they become quite large, i.e., the best analogue may occasionally fit the proxies rather badly.

Local differences over time become more apparent in Figure 4. Differences between local proxy series and the local analogue series are generally relatively small for proxy locations included in the analogue search. However, they are large not only for the proxies excluded because of lack of a signal but they are especially large for the central European region. The boxplot in the bottom right panel summarizes these interannual differences emphasizing the differences between included and excluded proxies.

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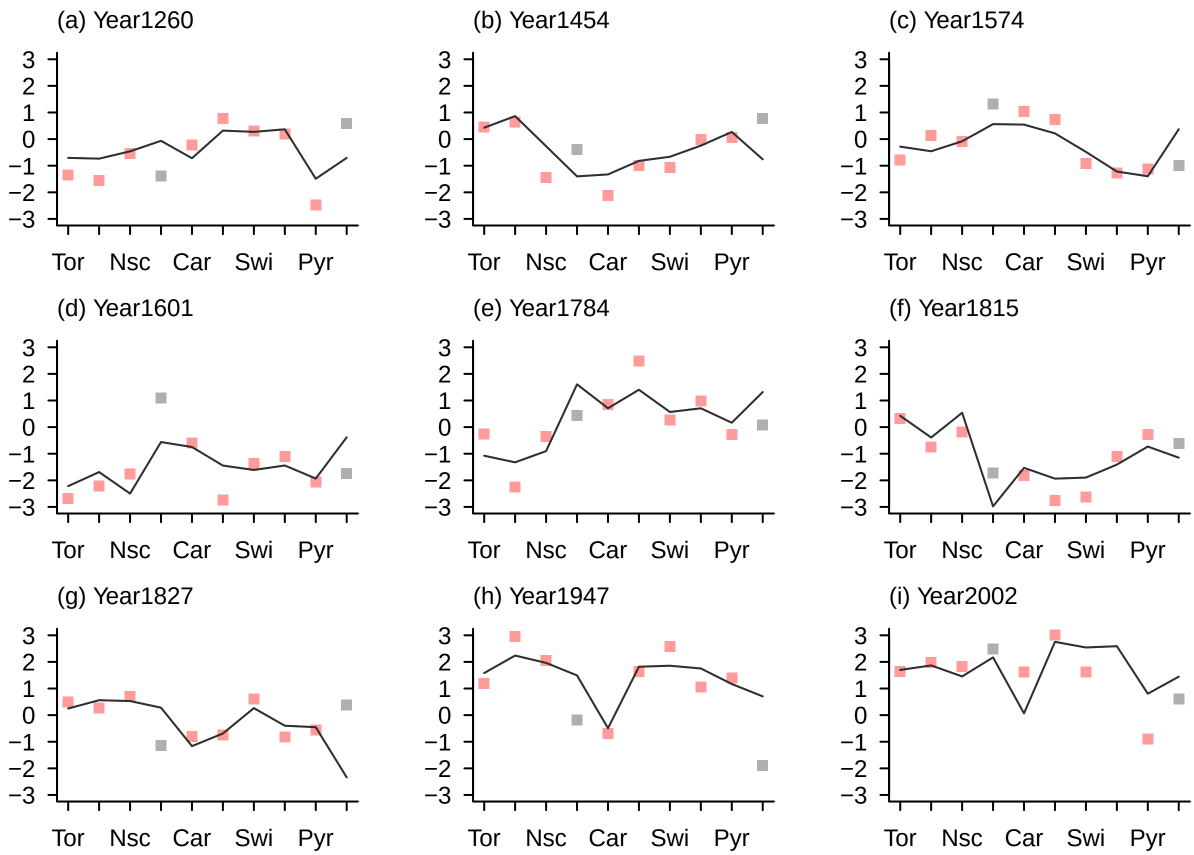

Figure 3. Normalised proxy values (squares) for proxies included (red) and excluded (grey) and the values of the best analogue for selected years (lines). Proxy locations on x-axes are from PAGES 2k Consortium (2013): Tor92, Torneträsk, Sweden, Jae11, Jämtland, Sweden, Nsc12, Northern Scandinavia, Tat12, greater Tatra region, Slovakia, Car09, Carpathian, Romania, Aus11, Alps, Austria, Swi06, Alps, Switzerland, Fra12, Alps, France, Pyr12, Pyrenees, Spain, Alb12, Albania.

The lack of signal for the Albanian and Tatra proxies becomes apparent in the strong multidecadal variability in the differences between local proxies and local analogue values. The data from the Tatra even shows multicentennial variations in the local differences. On the other hand, some structures are also apparent in the differences for the proxies included in the analogue search. Indeed, the Swiss Alps also show a small amplitude multicentennial variation in their local differences. Differences appear to be smallest for the Carpathian proxies.

The general agreement between the Euro 2k and the analogue reconstruction is another encouraging sign that the analogue method is a valid reconstruction tool at least for the considered time-period and regional focus. The strong local deviations at excluded locations however challenge how well the included proxies really represent the European domain and its intra-regional relations.

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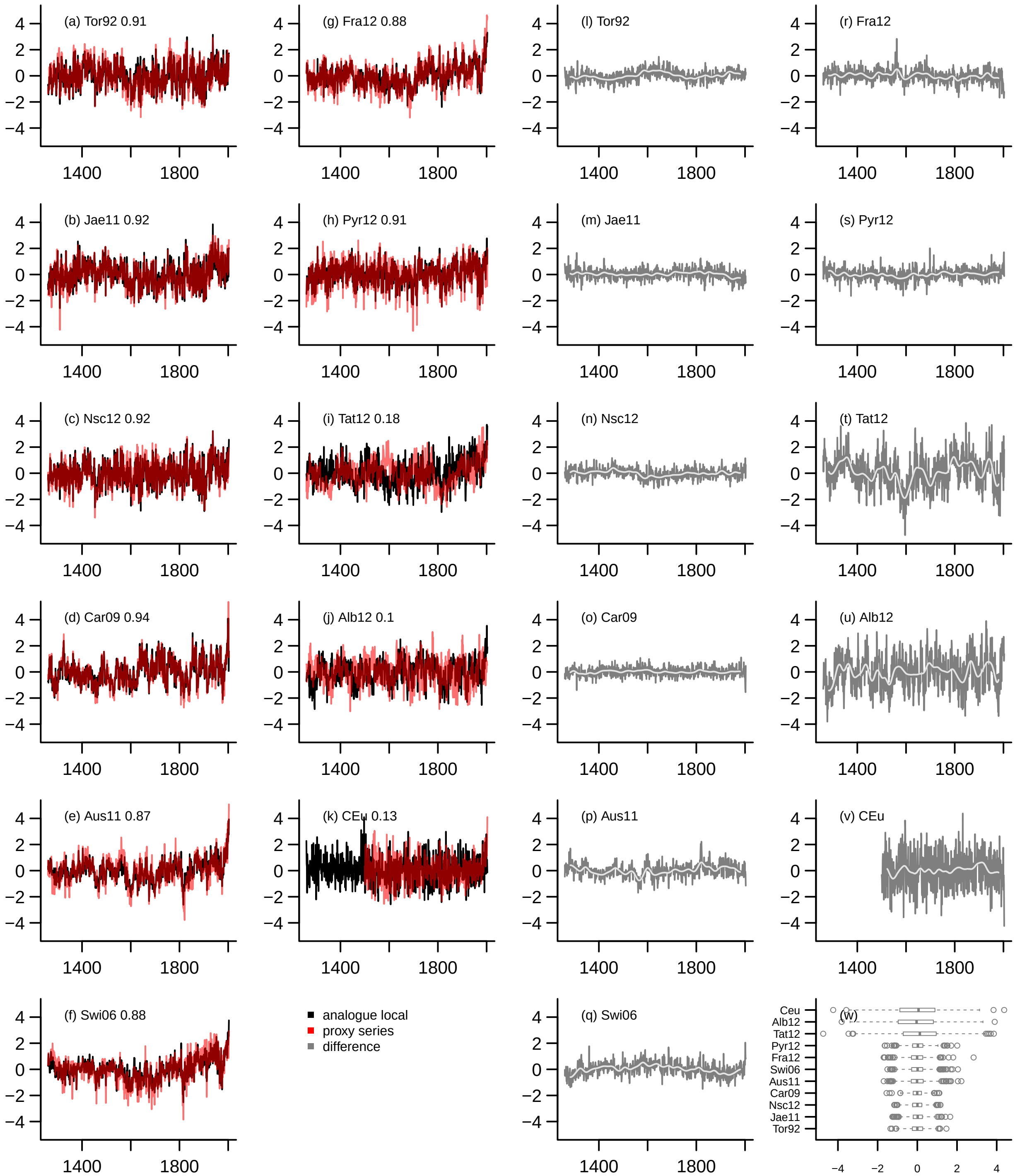

Figure 4. Left two columns, local grid-point series for the best analogue in black, proxy series in red. Right two columns, differences in grey. Bottom right panel: Boxplot for the differences for individual locations. Proxies are: Tor92, Torneträsk, Jae11, Jämtland, Nsc12, Northern Scandinavia, Tat12, greater Tatra region, Car09, Carpathian, Aus11, Alps, Swi06, Alps, Fra12, Alps, Pyr12, Pyrenees, Alb12, Albania. CEu is the Central Europe data. All data is from the normalised series and thus dimensionless. X-axes are years CE.

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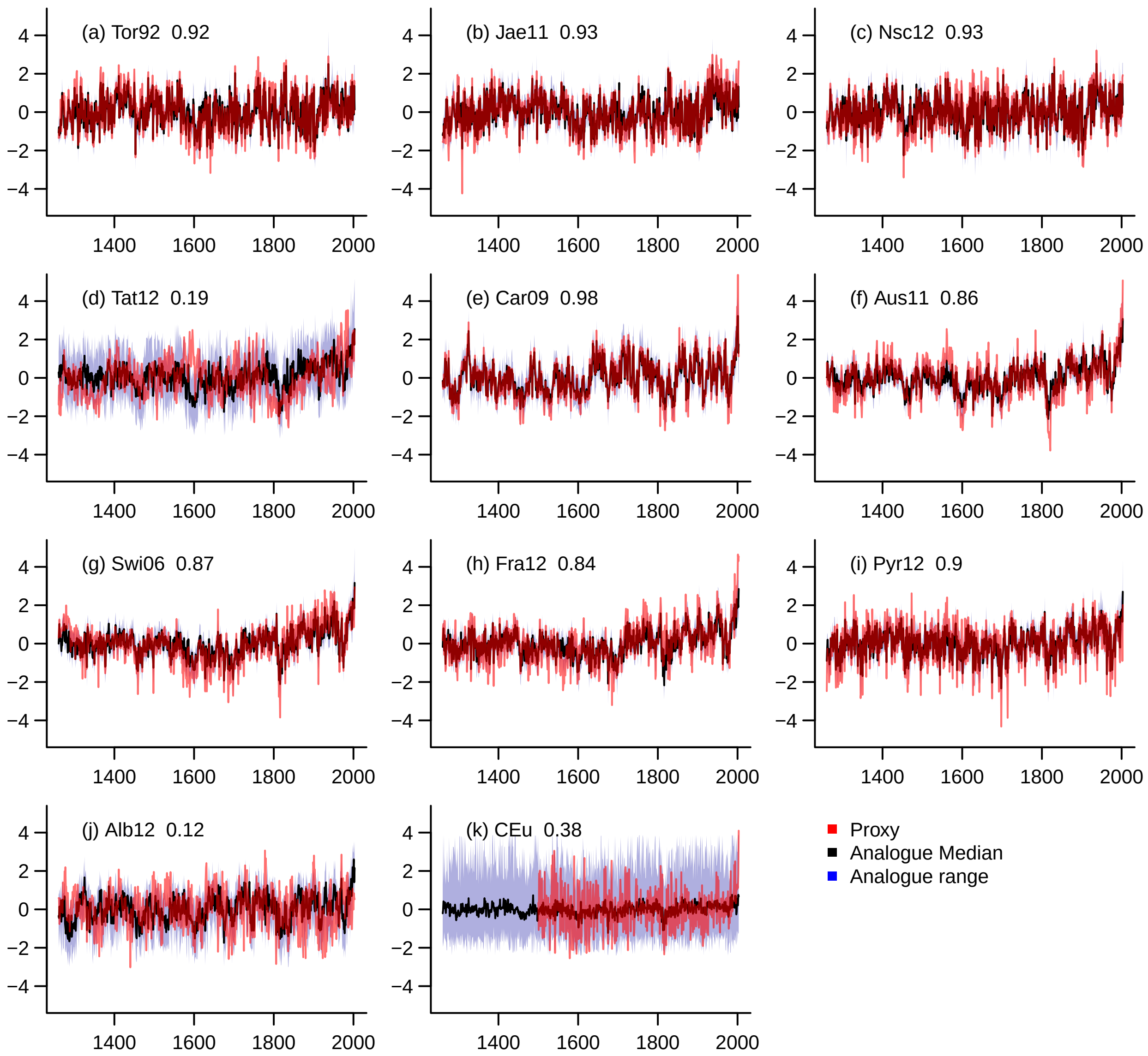

Figure 5. Analogue reconstruction values at the locations of the Euro 2k-proxies. Shown are the normalized proxies in red, the median of 39 analogue values in black and the full range of the 39 local analogues in blue. X-axes are years CE.

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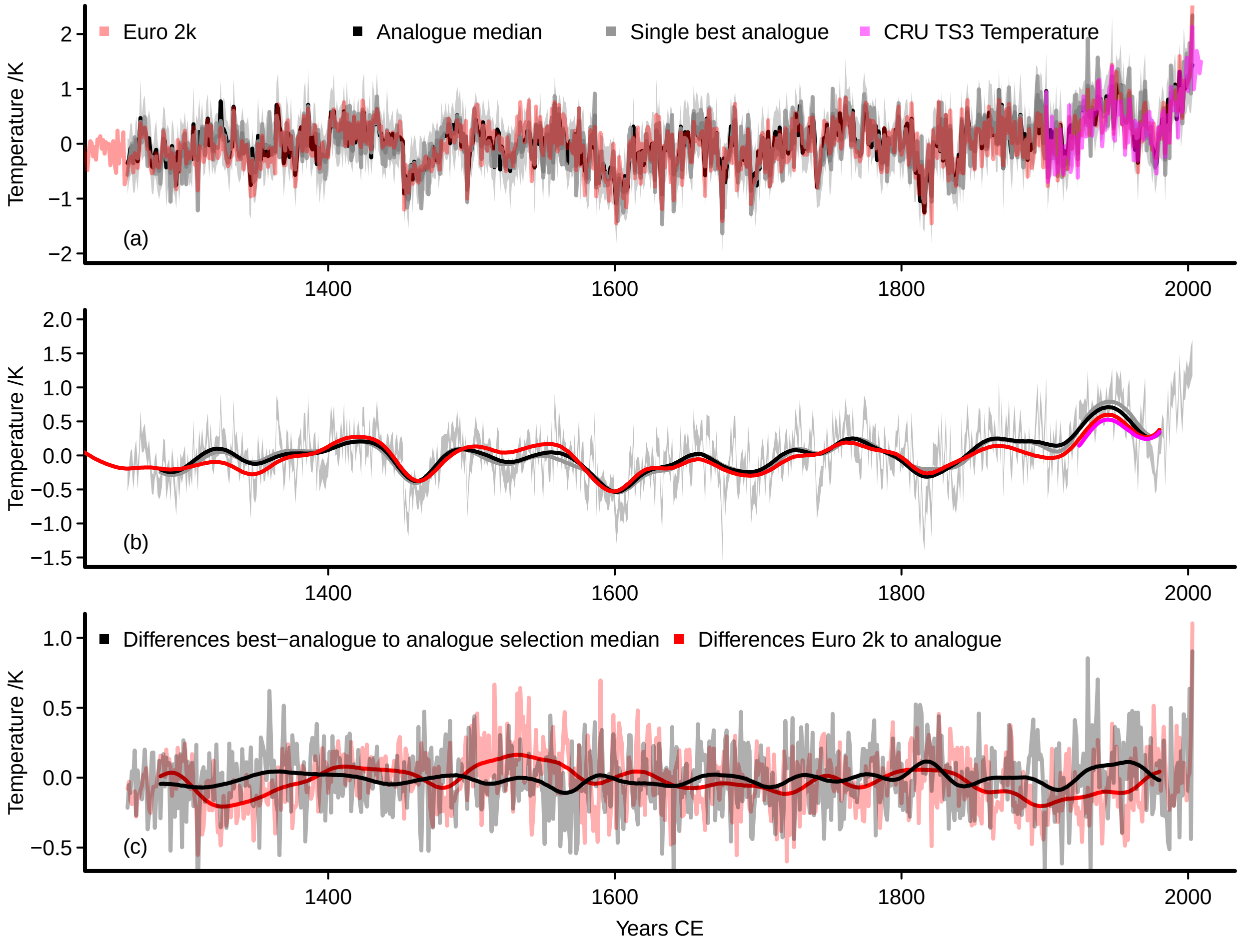

Figure 6. Summary of the analogue reconstruction for 39 best analogues. **(a)**: the interannual rescaled temperature reconstruction median in black and the range of the 39 analogues in grey; the grey line is the single best-analogue reconstruction; the red line is the Euro 2k-reconstruction; magenta is the CRU temperature adjusted to the mean of the reconstruction-median over the CRU period. **(b)**: as (a) but for 47-point Hamming filtered data, the grey range here is an interannual 50% uncertainty based on the variance of the 39 samples. **(c)**: Difference between the Euro 2k and the analogue reconstruction median in red and the difference between the best-analogue and the 39-analogue median and their respective smooths.

3.2 A set of 'good' analogues

Besides considering the single best analogue one can use a set of good analogues. One could base such a selection on an arbitrary number of, e.g., 10 analogues. However, in view of our considerations on the uncertainty of the local proxies, we use a specific uncertainty interval around the proxies. In our case, a $2.57\,SD_{noi}$ uncertainty interval for the proxy values allows for at least 39 analogues for each date. Thus, we select 39 analogues at the locations of the grid-points closest to the proxy-locations.

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Figure 5 presents local results for the analogue search reconstruction for the case of a fixed number of analogues. Correlations between the proxies and the reconstructed local series medians are between 0.84 and 0.98 for the anchor locations of the reconstruction. They are weak for the two locations excluded, i.e., Tatra and Albania. Visually there is good agreement and the range of reconstructed values is relatively narrow. However, there are also quite obvious mismatches, e.g., 16th century warmth in the Austrian Alps and, more frequently, individual very cold excursions, which are not matched in the analogues (Figure 5). Plotting local analogue data against the proxy series highlights how commonly the reconstruction median and random individual analogue members do not match the extreme values of the proxies (not shown).

Figure 5k shows the comparison for the spatial average temperature for the Central European area. This mean is computed over the grid-points from 7.5E to 18.75E and 46.4N and 50.1N in the coarse resolution model data. This domain obviously represents a larger area than the data by Dobrovolný et al. (2010). There is not any identifiable variability in the uncertainty envelope and consequently also the median shows very little variability. Nevertheless the variability is comparable between central European data for the analogue reconstruction and the original record if one considers individual members. Although the temporal variations of the median are muted the median-record still correlates notably but not strongly with the central European data of Dobrovolný et al. (2010).

Figure 6 highlights again a good agreement between the chosen analogue approach and the Euro 2k-reconstruction. Indeed the median of the fixed-number analogue-ensemble correlates slightly better with the Euro 2k-reconstruction at $r \approx 0.89$ compared to the single best analogue ($r \approx 0.82$). The variability of the median, however, is notably smaller than for either the Euro 2k or the best analogue data. Similarly, while the range of the best analogue is comparable to the Euro 2k-reconstruction, the range of the 39-analogue ensemble median is strongly reduced compared to both other series. Therefore, using a set of analogues to produce a reconstruction suppresses variability. The coldest values are only slightly warmer but the warmest values are about one degree Kelvin colder than for the other two series.

Although the uncertainty of the regional average for Central Europe shows a wide uncertainty for the 39 analogues, the full domain reconstruction has a narrow 50% uncertainty range. It is nearly impossible to visually identify the 50% range for the smoothed data (not shown), i.e. based on the ensemble variability of the smoothed ensemble of 39 analogues. Thus, in some sense the included proxies anchor the reconstruction to a very narrow range of variability if we choose a fixed number of analogues.

Interannual differences between the single best-analogue reconstruction and the median of the 39-analogue reconstruction appear to be of similar size as the interannual differences between the Euro 2k-reconstruction and the 39-analogue median. The smoothed representations align however quite well for the two different analogue approaches. On the other hand there are some systematic differences between the 39-analogue median and the Euro 2k-reconstruction in the smoothed version particularly in the 14th and 16th centuries and since approximately the year 1850. Differences between the two analogue approaches do not show such systematic differences except maybe for the early 20th century. Both analogue approaches appear to overestimate the warming trend since the early 19th century. This is more pronounced in the single best reconstruction compared to the median of the 39 analogues, for which we already noted the reduced variability.

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The coldest and warmest periods are very similar in the 39-analogue reconstruction compared to the best-analogue version. Again, coldest conditions on decadal, 30-year, and century time-scales occur mainly in the 17th century (not shown). This holds for the median as well as the coldest and warmest analogue estimates for the periods. For the period before 1850, the warmest periods in the 39-analogue reconstruction are commonly centred in the early second half of the 18th century (not shown).

Again, we find summer cooling following some well dated tropical volcanic eruptions but others barely leave a signal in the European mean data based on a superposed epoch analysis (not shown). For spatial fields, similarly, there is not a distinct signal of post-eruption summer cooling. The potential wide range of analogues even allows for some regional warming.

3.3 Analogues within $1SD_{noi}$

In addition to using a fixed set of best analogues we can consider only those analogues falling within a certain uncertainty interval around all of the original proxies for each date. This will result in an uneven number of analogues at each individual date. This section presents the results for our setup and a fixed one noise-standard-deviation interval around the proxy values. The larger the interval the less likely is that the method fails in finding analogues but larger intervals also imply that the number of analogues may become exceedingly large for certain dates. As mentioned above, the one standard deviation interval has a maximal number of 2105 possible analogues which one may already rate as too many.

Figure 7 displays the results for such an analogue reconstruction collecting all analogues within one noise-standard-deviation around the proxy values. Again there is good agreement between the analogue reconstruction and the Euro 2k-reconstruction. Blue lines in the upper panels of Figure 7 show one single member of the reconstruction ensemble which also compares quite well to the Euro 2k-reconstruction.

As mentioned before, the smaller the uncertainty-interval, the more likely the method is to fail in finding suitable analogues. This becomes obvious when considering the smoothed estimates. This way of constraining the analogue space quite frequently fails to provide any analogue at all. Small ticks at the time-axes of Figure 7 show that such failures appear to cluster in the 13th and 14th centuries, in the 16th and 17th centuries and in the early 19th century. A number of these are years with strong forcing from volcanic eruptions (compare Sigl et al., 2015).

Another period without suitable analogues occurs at the end of the considered period after the year 2000, which is unsurprising as the European temperature slowly leaves the temperature range observed in the previous approximately 750 years. However, considering the results of Jungclaus et al. (2010, e.g., their Figure 3) one might have hoped that the COSMOS-millennium simulation ensemble includes analogues also matching the recent patterns. Occasionally, there is only one analogue, which results in additional gaps in the standard-deviation based uncertainty envelope.

The bottom panel of Figure 7 shows in grey the full range of the found analogues at each time step and in blue a two standard-deviation interval of the analogue variability. The range of analogues reflects to a good part simply the number of available analogues. The relatively constant $2SD$ range is notably narrower than the full range here.

The occasional failure of the method to find analogues complicates any attempt to identify coldest centuries. That is, the validity of any identified period is limited and, thus, the exercise is of reduced value. However, the coldest decades and 30-year

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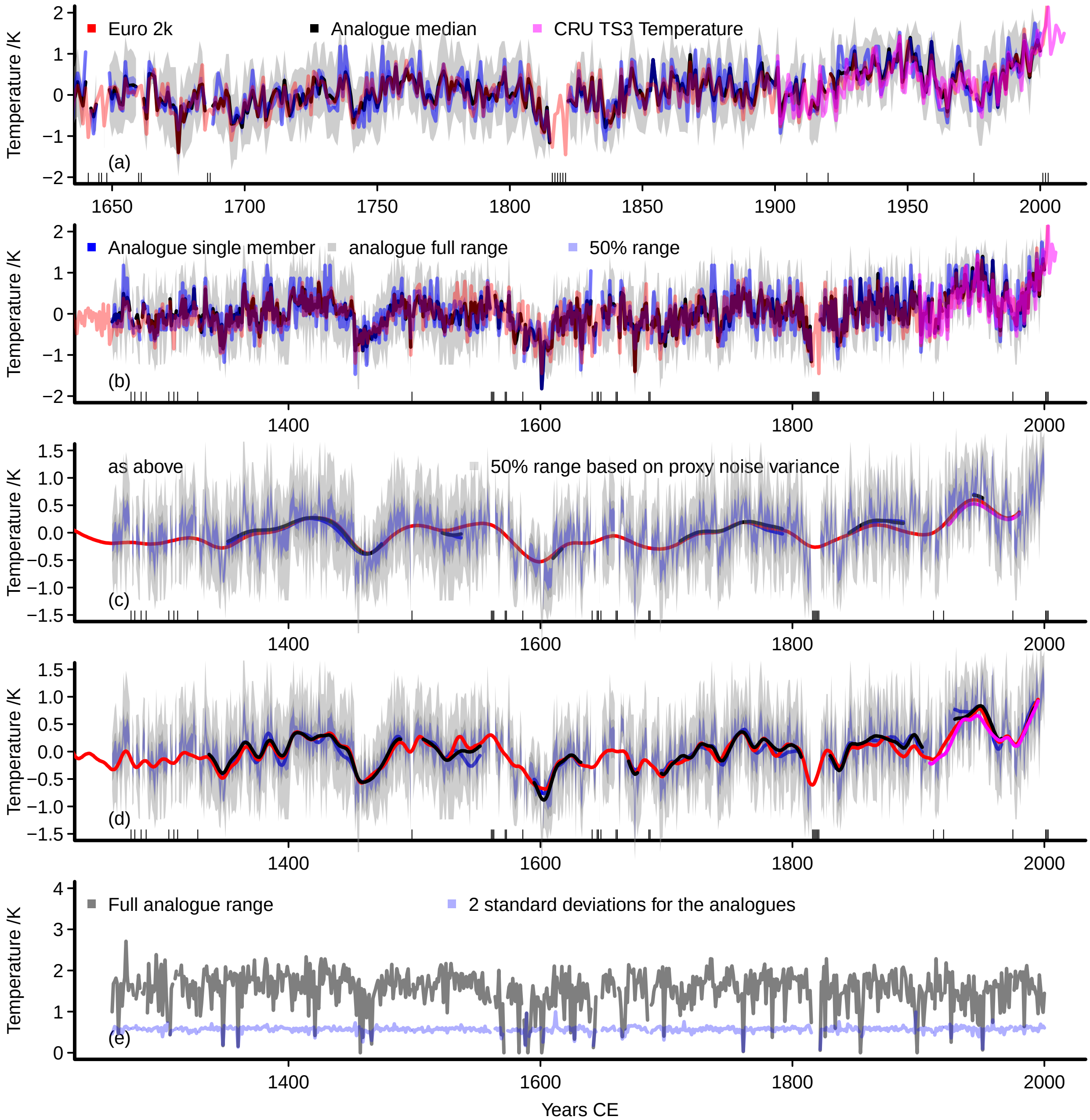

Figure 7. Summary of the analogue reconstruction based on an $1SD_{noi}$ uncertainty of the proxies. **(a)**: Interannual data for the period since about 1650: red, the Euro 2k-reconstruction; black, the analogue median; blue line, a single analogue member, blue shading, 50% range around the analogue median based on variability of the analogues, grey shading, the full range of analogues; marks at horizontal axis mark unsuccessful analogue searches. **(b)**: as (a) but for the full period; legends for (a) and (b) are split up between the two panels. **(c)**: As (b) for 47-point Hamming filtered data, but the second, narrower grey envelope is for a 50% uncertainty based on the square root of the noise variances. **(d)**: As (c) but for 17-point Hamming filtered data. **(e)**: Grey, range of the interannual analogues, blue, 2 standard deviations for the analogues.

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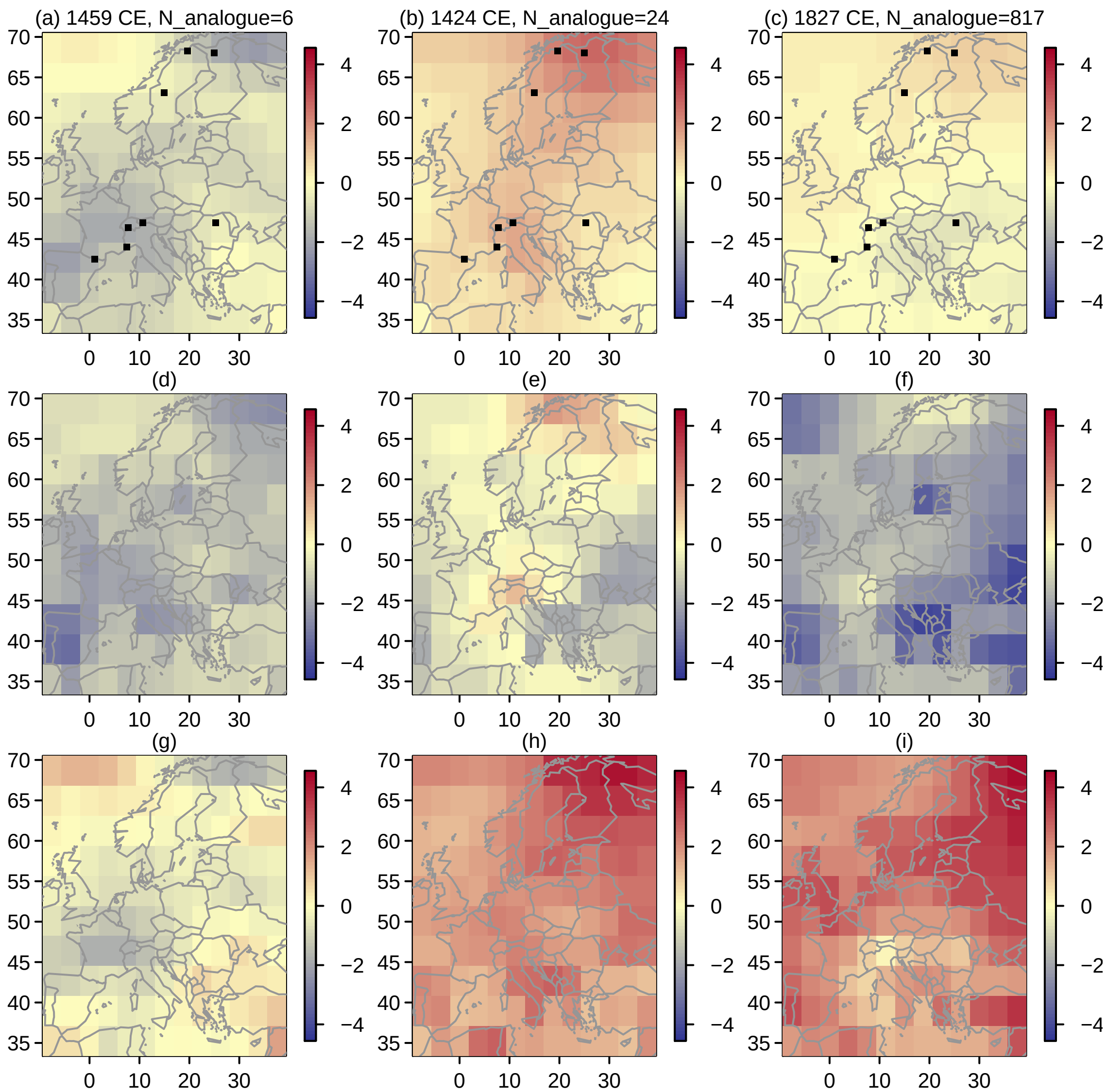

Figure 8. Analogue fields for three reconstructed cases with different numbers of analogues, color bars are temperature anomalies in Kelvin relative to the full period. From left to right, 1459 CE with 6 analogues, 1424 CE with 24 analogues, and 1827 CE with 817 analogues. From top to bottom, mean, local minimum and local maximum. Black dots signal the proxy locations in the top row.

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periods again are in the early 17th century. We find the warmest periods usually centred about the early 15th century for the period before 1850 CE. However, considering only the warmest estimates of the envelope, the warmest decade occurs in the second half of the 18th century.

The lack of appropriate analogues also hampers evaluating the response to well dated tropical volcanic eruptions. That is, e.g., there are not any analogues available for the year without summer 1816 CE. Otherwise, the common feature is again that some eruptions appear to have resulted in European summer cooling while there is no identifiable imprint for other eruptions in our European mean data (not shown). Comparing spatial fields for this reconstruction, anomalies are more homogeneous but also smaller than for the reconstruction from 39 good analogues (not shown). While we find cooling, the wide range of the analogues also allows for notable warming for some eruptions.

Up until now, we concentrated on time-series. Figure 8 shows how the analogue reconstruction can provide diverse spatial representations for the same set of proxy-values. It can give several different reconstructions, which strongly differ from each other. The example years are chosen to represent a rather cold, a rather warm, and an approximately average year. Therefore the top row shows the mean of the found analogues for the three cases of 1459 CE, 1424 CE, and 1827 CE. Incidentally these are also three years for which we find few, i.e. 6, reasonable, i.e. 24, and as many as 817 analogues in a one standard-deviation interval. Black dots in the top row show the original proxy locations. Note that the Figure displays temperature anomalies from the mean over the full period in Kelvin. The subsequent rows add the local minimum and maximum values respectively.

It is surprising that, e.g., the proxies anchor the year 1827 in Turkey only within a range of up to 8 Kelvin for the more than 800 analogues. Even central Scandinavia may be rather cold or rather warm although it should be constrained by three proxy records. Indeed the best analogue for that year is close to the proxies (compare Figure 3).

The 24 analogues for the year 1424 have a tendency to warm values but again warm and cold conditions are found within a one standard deviation interval around our proxy anchors for south-eastern and south-western Europe. On the other hand the six analogues available for the year 1459 mostly give slightly cold conditions over wide parts of the domain and especially for continental Europe.

The fact that the fixed uncertainty analogue search commonly fails in finding suitable analogues obviously reduces its value if we are interested in complete reconstruction series. However, such deficiencies also provide valuable information about how well our pool of analogues represents the variability recorded by the proxies within a certain interval of confidence.

3.4 Comparison to station data

Station data allow to evaluate our reconstruction against sources of information independent of the proxies or other reconstructions. The Berkeley Earth project (BEST Muller et al., 2013) provides regionally representative series, which we use in the following for a short comparison. We choose those regionally representative series close to locations of long instrumental records. Figure 9 shows a selection of such comparisons with the median of the one standard deviation reconstruction ensemble.

Correlations are often reasonable between the reconstructed median data close to locations of the long instrumental records with the regionally representative data series from the BEST project (Muller et al., 2013), see numbers in panels of Figure 9. Correlations are largest in Scandinavia and around the Alps. Both regions are where most proxy records are located.

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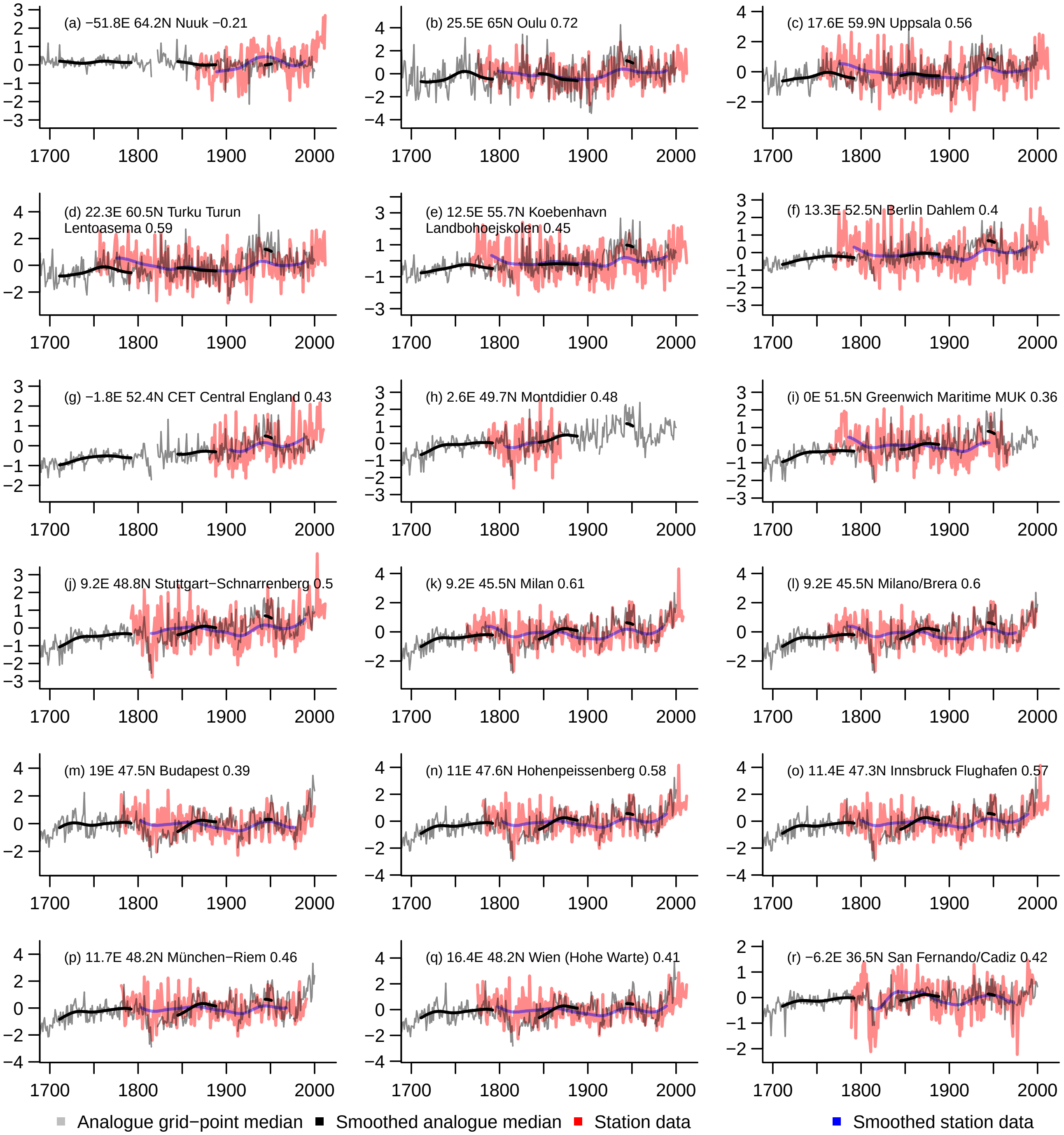

Figure 9. Comparison of local grid-point analogue data with an arbitrary selection of regionally representative data from BEST. Location, station name, and correlation over available station data are at the top of the panels. Grey and black, interannual and smoothed analogue median. Red and blue, station data and its smooth. X-axes are years CE. Y-axes are temperature anomalies in degree Kelvin relative to the period where both datasets are available.

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Comparing the data series, however, indicates notable shortcomings of the reconstruction median. The reconstruction median often overestimates the recent warming trend and the median shows notably less variability than the BEST-series. The underestimation of the variability on the other hand leads occasionally to an underestimation of the most recent warm anomalies. High latitude series from the reconstruction may also show notably strange variability (see, e.g., for Nuuk in the top-left panel). There are also cases where both series appear to agree quite well over the period when both are available. Examples are the Central England Temperature and Montdidier.

4 Summary and Discussions

Earlier proxy surrogate reconstructions from the analogue method usually considered the single best match or a small set of best fits to reconstruct past climate states compliant with limited local proxy information. The method traditionally neglects the uncertainty of the final estimate.

Testing the analogue method against a prior reconstruction for the European domain shows that it indeed allows to reconstruct past climate variability comparably to more common approaches. It appears even to appropriately capture the intra-proxy variability and the proxy-variability over time. This holds for either a single best or multiple good analogues.

If we consider only analogues within a certain interval around the proxy data, we still obtain a good reconstruction compared to the earlier Euro 2k-reconstruction. We further show that this analogue reconstruction also captures rather well independent data derived from station observations. However, problems arise in the case of a fixed uncertainty interval around the proxies. In this case, we are not able to obtain good analogues for some dates. Similarly to Franke et al. (2010, see also Gómez-Navarro et al., 2014 and Annan and Hargreaves, 2012) the quality of the reconstruction diminishes further away from the anchoring proxies.

Uncertainty estimates are available for each of the three reconstruction approaches. One approach to quantify the uncertainty of the single best analogue is the mean standard error between the reconstructed values closest to the proxy locations and the proxy values. Another and by construction wider uncertainty estimate bases on the correlation between the proxies and local temperature observations. The square root of the sum over the Var_{noi}, i.e. the residual noise variability, for the invdidual proxies divided by the number of proxies gives a simple uncertainty estimate for the analogue search that by construction should be an upper limit for the best analogue deviations if the best analogues are within this range.

For a reconstruction of a constant number of good analogues the ensemble range gives an uncertainty interval. If we use only analogues within a certain limit of noise standard deviations, the range of the ensemble values provides an uncertainty estimate, with the square root of the sum over the Var_{noi} for the invdidual proxies divided by the number of proxies again giving an upper limit. Note also that these estimates generally are local uncertainties. Only the ensemble envelopes reflect the mean uncertainty.

We only consider complete proxy records starting at the same date with the same temporal resolution. However, the analogue method does not rely on these assumptions. It easily compensates for missing values and data with different resolutions.

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Gómez-Navarro et al. (2017) and Jensen et al. (2018) provide some analyses in this direction. The method however depends strongly on the pool of available analogues and the criteria for selection of analogues.

While we focussed on the temperature fields, it is easy to additionally reconstruct other variables that are compatible with the temperature proxy records, since the climate models do not only simulate surface temperature but the full climate/weather situations. This could produce a relevant probabilistic estimate of these past situations. However, the reliability of these samples obviously depends on the strength of the link between the local temperature and other large scale fields. Similarly it is possible to obtain larger scale climate estimates compliant with the regional information, e.g., hemispheric means, and compare these to situations compliant with other proxy information. A caveat in all these considerations are the findings by Annan and Hargreaves (2012), who note that reconstructions by comparable methods may not give the correct posterior distribution if we have a large number of proxies with small uncertainty, while if we have only few proxies with large uncertainties, the final reconstructed estimate may be not very meaningful due to a lack of accuracy.

We have to note that the reconstruction neglects possible information about the past climate forcing trajectory. This has implications for dynamical inferences, which may be misleading. While one can account for this by including the forcing reconstruction in the anchoring dataset, this reduces the pool of potential analogues. Furthermore, all results depend on the consistency and quality of the pool of analogues, i.e. the simulations and the underlying sophisticated climate models.

Applications of the analogue method commonly only focus on the best analogue. The failure to find any analogue and the occurrence of multiple good analogues raise the issues of extrapolation and interpolation of the analogue pool and the analogue ensemble. Interpolation of analogues may be of interest for obtaining one optimal representation for the reconstruction. More crucially, extrapolation is one solution to obtain reconstructions for situations, e.g., extremes, which are not included in the pool of potential analogues. Extrapolation of the current pool may be possible by generating synthetic analogues. Data science methods may be available to do this.

5 Concluding remarks

Proxy surrogate reconstructions from the analogue method often neglect that the proxies and, in turn, the reconstruction are uncertain estimates. Here, we suggest uncertainty estimates for single best-analogue reconstructions as well as analogue reconstructions from multiple good analogues. We are primarily interested in the case where we only consider analogues which fall within a certain uncertainty interval of the original proxies.

We compare reconstructions and uncertainty estimates to a previously published reconstruction. This evaluation suggests that the analogue approaches capture the variability as well as a composite-plus-scaling approach.

The analogue reconstructions also appear to capture the intra-proxy variability and the proxy-variability. Similarly, our results suggest that our approach compares well to independent data.

If we only use analogues, which comply with the proxies within a certain uncertainty interval, the problem arises that there may be no compliant candidates in the pool of simulated fields.

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Upscaling the local proxies to obtain larger scale climate information holds many opportunities to infer information about past climate states. However, one has to add relevant estimates of uncertainty to provide meaningful information.

Data availability. The simulation data is available from the World Data Center for Climate (WDCC) at https://cera-www.dkrz.de/WDCC/ui/cerasearch/project?acronym=MILLENNIUM_COSMOS (last accessed, 21 May 2019). The Euro 2k reconstruction in the version of PAGES 2k Consortium (2013) and the uncerlying proxies are available from https://doi.org/10.1038/ngeo1797 or alternatively https://www.ncdc.noaa.gov/paleo-search/study/14188 (both last accessed, 21 May 2019). The Euro 2k reconstructions of Luterbacher et al. (2016) can be found at https://www.ncdc.noaa.gov/paleo-search/study/19600 (last accessed 21 May 2019). Data for assessing the response to volcanic eruptions from Sigl et al. (2015) is available from https://doi.org/10.1038/nature14565 (last accessed 21 May 2019). We use version CRU TS 3.10 of the observational CRU-data (Harris et al., 2014; University of East Anglia Climatic Research Unit et al., 2017), 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 Berkeley Earth project data (BEST Muller et al., 2013) can be obtained from http://berkeleyearth.org/ (last accessed, 22 May 2019). Relevant results of the present study will be uploaded to the Open Science Framework at https://osf.io/embdh/.

Author contributions. Oliver Bothe devised the analyses, performed them, and wrote the first draft. O.B. and Eduardo Zorita discussed the results and revised the manuscript.

Competing interests. The authors declare no competing interests.

Acknowledgements. Funding in the projects PRIME2 and PALMOD (www.palmod.de) made the completion of this study possible. This study is a contribution to PALMOD, and to the PAGES 2k Network, especially its PALEOLINK project. We acknowledge the service of the World Data Center for Climate in providing the simulation data and of the NOAA Centers for Environmental Information for providing the reconstruction data by Luterbacher et al. (2016) and PAGES 2k Consortium (2013).

https://doi.org/10.5194/cp-2019-81
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References

Annan, J. D. and Hargreaves, J. C.: Identification of climatic state with limited proxy data, Climate of the Past, 8, 1141–1151, https://doi.org/10.5194/cp-8-1141-2012, 2012.

Bierstedt, S. E., Hünicke, B., Zorita, E., Wagner, S., and Gómez-Navarro, J. J.: Variability of daily winter wind speed distribution over Northern Europe during the past millennium in regional and global climate simulations, Climate of the Past, 12, 317–338, https://doi.org/10.5194/cp-12-317-2016, 2016.

Bothe, O., Wagner, S., and Zorita, E.: Inconsistencies between observed, reconstructed, and simulated precipitation indices for England since the year 1650 CE, Climate of the Past, 15, 307–334, https://doi.org/10.5194/cp-15-307-2019, 2019.

Dahl-Jensen, D., Capron, E., Vallelonga, P., and Roche, D.: Past4Future: European interdisciplinary research on past warm climate periods, PAGES Magazine, 23, 3, 2015.

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

Evans, M. N., Tolwinski-Ward, S. E., Thompson, D. M., and Anchukaitis, K. J.: Applications of proxy system modeling in high resolution paleoclimatology, Quaternary Science Reviews, 76, 16–28, https://doi.org/10.1016/j.quascirev.2013.05.024, 2013.

Evans, M. N., Smerdon, J. E., Kaplan, A., Tolwinski-Ward, S. E., and González-Rouco, J. F.: Climate field reconstruction uncertainty arising from multivariate and nonlinear properties of predictors, Geophysical Research Letters, 41, 9127–9134, https://doi.org/10.1002/2014GL062063, 2014.

Fernández-Donado, L., González-Rouco, J. F., Raible, C. C., Ammann, C. M., Barriopedro, D., García-Bustamante, E., Jungclaus, J. H., Lorenz, S. J., Luterbacher, J., Phipps, S. J., Servonnat, J., Swingedouw, D., Tett, S. F., Wagner, S., Yiou, P., and Zorita, E.: Large-scale temperature response to external forcing in simulations and reconstructions of the last millennium, Climate of the Past, 9, 393–421, https://doi.org/10.5194/cp-9-393-2013, 2013.

Franke, J., González-Rouco, J. F., Frank, D., and Graham, N. E.: 200 years of European temperature variability: insights from and tests of the proxy surrogate reconstruction analog method, Climate Dynamics, 37, 133–150, https://doi.org/10.1007/s00382-010-0802-6, 2010.

Gómez-Navarro, J., Werner, J., Wagner, S., Luterbacher, J., and Zorita, E.: Establishing the skill of climate field reconstruction techniques for precipitation with pseudoproxy experiments, Climate Dynamics, pp. 1–19, https://doi.org/10.1007/s00382-014-2388-x, 2014.

Gómez-Navarro, J. J., Montávez, J. P., Wagner, S., and Zorita, E.: A regional climate palaeosimulation for Europe in the period 1500–1990 – Part 1: Model validation, Climate of the Past, 9, 1667–1682, https://doi.org/10.5194/cp-9-1667-2013, 2013.

Gómez-Navarro, J. J., Bothe, O., Wagner, S., Zorita, E., Werner, J. P., Luterbacher, J., Raible, C. C., and Montávez, J. P.: A regional climate palaeosimulation for Europe in the period 1500-1990 - Part 2: Shortcomings and strengths of models and reconstructions, Climate of the Past, 11, 1077–1095, https://doi.org/10.5194/cp-11-1077-2015, 2015.

Gómez-Navarro, J. J., Zorita, E., Raible, C. C., and Neukom, R.: Pseudo-proxy tests of the analogue method to reconstruct spatially resolved global temperature during the Common Era, Climate of the Past, 13, 629–648, https://doi.org/10.5194/cp-13-629-2017, 2017.

Graham, N., Hughes, M., Ammann, C., Cobb, K., Hoerling, M., Kennett, D., Kennett, J., Rein, B., Stott, L., Wigand, P., and Xu, T.: Tropical Pacific – mid-latitude teleconnections in medieval times, Climatic Change, 83, 241–285, https://doi.org/10.1007/s10584-007-9239-2, 2007.

https://doi.org/10.5194/cp-2019-81
Preprint. Discussion started: 5 July 2019

Graumlich, L. J.: A 1000-Year Record of Temperature and Precipitation in the Sierra Nevada, Quaternary Research, 39, 249–255, https://doi.org/10.1006/qres.1993.1029, 1993.

Guiot, J., Corona, C., and Members, E.: Growing Season Temperatures in Europe and Climate Forcings Over the Past 1400 Years, PLoS ONE, 5, e9972+, https://doi.org/10.1371/journal.pone.0009972, 2010.

Harris, I., Jones, P. D., Osborn, T. J., and Lister, D. H.: Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset, Int. J. Climatol., 34, 623–642, https://doi.org/10.1002/joc.3711, 2014.

Jackson, S. T. and Williams, J. W.: Modern Analogs In Quaternary Paleoecology: Here Today, Gone Yesterday, Gone Tomorrow?, http://dx.doi.org/10.1146/annurev.earth.32.101802.120435, 2004.

Jensen, M. F., Nummelin, A., Nielsen, S. B., Sadatzki, H., Sessford, E., Risebrobakken, B., Andersson, C., Voelker, A., Roberts, W. H. G., Pedro, J., and Born, A.: A spatiotemporal reconstruction of sea-surface temperatures in the North Atlantic during Dansgaard–Oeschger events 5–8, Climate of the Past, 14, 901–922, https://doi.org/10.5194/cp-14-901-2018, 2018.

Jungclaus, J.: MPI-M Earth System Modelling Framework: millennium full forcing experiment (ensemble member 1)., http://cera-www.dkrz.de/WDCC/ui/Compact.jsp?acronym=mil0010, 2008a.

Jungclaus, J.: MPI-M Earth System Modelling Framework: millennium full forcing experiment (ensemble member 2)., http://cera-www.dkrz.de/WDCC/ui/Compact.jsp?acronym=mil0012, 2008b.

Jungclaus, J.: MPI-M Earth System Modelling Framework: millennium full forcing experiment (ensemble member 3)., http://cera-www.dkrz.de/WDCC/ui/Compact.jsp?acronym=mil0013, 2008c.

Jungclaus, J.: MPI-M Earth System Modelling Framework: millennium full forcing experiment (ensemble member 4)., http://cera-www.dkrz.de/WDCC/ui/Compact.jsp?acronym=mil0014, 2008d.

Jungclaus, J.: MPI-M Earth System Modelling Framework: millennium full forcing experiment (ensemble member 5)., http://cera-www.dkrz.de/WDCC/ui/Compact.jsp?acronym=mil0015, 2008e.

Jungclaus, J.: MPI-M Earth System Modelling Framework: millennium full forcing experiment using solar forcing of Bard (ensemble member 2)., http://cera-www.dkrz.de/WDCC/ui/Compact.jsp?acronym=mil0025, 2009a.

Jungclaus, J.: MPI-M Earth System Modelling Framework: millennium full forcing experiment using solar forcing of Bard (ensemble member 3)., http://cera-www.dkrz.de/WDCC/ui/Compact.jsp?acronym=mil0026, 2009b.

Jungclaus, J. and Esch, M.: mil0021: MPI-M Earth System Modelling Framework: millennium full forcing experiment using solar forcing of Bard, http://cera-www.dkrz.de/WDCC/ui/Compact.jsp?acronym=mil0021, 2009.

Jungclaus, J. H., Keenlyside, N., Botzet, M., Haak, H., Luo, J. J., Latif, M., Marotzke, J., Mikolajewicz, U., and Roeckner, E.: Ocean Circulation and Tropical Variability in the Coupled Model ECHAM5/MPI-OM, J. Climate, 19, 3952–3972, https://doi.org/10.1175/JCLI3827.1, 2006.

Jungclaus, J. H., Lorenz, S. J., Timmreck, C., Reick, C. H., Brovkin, V., Six, K., Segschneider, J., Giorgetta, M. A., Crowley, T. J., Pongratz, J., Krivova, N. A., Vieira, L. E., Solanki, S. K., Klocke, D., Botzet, M., Esch, M., Gayler, V., Haak, H., Raddatz, T. J., Roeckner, E., Schnur, R., Widmann, H., Claussen, M., Stevens, B., and Marotzke, J.: Climate and carbon-cycle variability over the last millennium, Climate of the Past, 6, 723–737, https://doi.org/10.5194/cp-6-723-2010, 2010.

Lohmann, K., Mignot, J., Langehaug, H. R., Jungclaus, J. H., Matei, D., Otterå, O. H., Gao, Y. Q., Mjell, T. L., Ninnemann, U. S., and Kleiven, H. F.: Using simulations of the last millennium to understand climate variability seen in palaeo-observations: similar variation of Iceland–Scotland overflow strength and Atlantic Multidecadal Oscillation, Climate of the Past, 11, 203–216, https://doi.org/10.5194/cp-11-203-2015, 2015.

https://doi.org/10.5194/cp-2019-81
Preprint. Discussion started: 5 July 2019

Climate of the Past
Discussions

Lorenz, E. N.: Atmospheric Predictability as Revealed by Naturally Occurring Analogues, http://dx.doi.org/10.1175/1520-0469(1969)26<636:APARBN>2.0.CO;2, 1969.

Luterbacher, J., Koenig, S. J., Franke, J., van der Schrier, G., Zorita, E., Moberg, A., Jacobeit, J., Della-Marta, P. M., Küttel, M., Xoplaki, E., Wheeler, D., Rutishauser, T., Stössel, M., Wanner, H., Brázdil, R., Dobrovolný, P., Camuffo, D., Bertolin, C., van Engelen, A., Gonzalez-Rouco, F. J., Wilson, R., Pfister, C., Limanówka, D., Nordli, Ø., Leijonhufvud, L., Söderberg, J., Allan, R., Barriendos, M., Glaser, R., Riemann, D., Hao, Z., and Zerefos, C. S.: Circulation dynamics and its influence on European and Mediterranean January–April climate over the past half millennium: results and insights from instrumental data, documentary evidence and coupled climate models, Climatic Change, 101, 201–234, https://doi.org/10.1007/s10584-009-9782-0, 2010.

Luterbacher, J., Werner, J. P., Smerdon, J. E., Fernández-Donado, L., González-Rouco, F. J., Barriopedro, D., Ljungqvist, F. C., Büntgen, U., Zorita, E., Wagner, S., Esper, J., McCarroll, D., Toreti, A., Frank, D., Jungclaus, J. H., Barriendos, M., Bertolin, C., Bothe, O., Brázdil, R., Camuffo, D., Dobrovolný, P., Gagen, M., García-Bustamante, E., Ge, Q., Gómez-Navarro, J. J., Guiot, J., Hao, Z., Hegerl, G. C., Holmgren, K., Klimenko, V. V., Martín-Chivelet, J., Pfister, C., Roberts, N., Schindler, A., Schurer, A., Solomina, O., von Gunten, L., Wahl, E., Wanner, H., Wetter, O., Xoplaki, E., Yuan, N., Zanchettin, D., Zhang, H., and Zerefos, C.: European summer temperatures since Roman times, Environmental Research Letters, 11, 24 001, https://doi.org/10.1088/1748-9326/11/2/024001, 2016.

Muller, R., Rohde, R., Jacobsen, R., Muller, E., and Wickham, C.: A New Estimate of the Average Earth Surface Land Temperature Spanning 1753 to 2011, Geoinformatics & Geostatistics: An Overview, 01, https://doi.org/10.4172/2327-4581.1000101, 2013.

Namias, J.: Remarks on Long Range Weather Forecasting, http://dx.doi.org/10.1080/00431672.1948.9933497, 1948.

Otto-Bliesner, B. L., Brady, E. C., Fasullo, J., Jahn, A., Landrum, L., Stevenson, S., Rosenbloom, N., Mai, A., and Strand, G.: Climate Variability and Change since 850 CE: An Ensemble Approach with the Community Earth System Model, Bulletin of the American Meteorological Society, 97, 735–754, https://doi.org/10.1175/BAMS-D-14-00233.1, 2016.

PAGES 2k Consortium: Continental-scale temperature variability during the past two millennia, Nature Geoscience, 6, 339–346, https://doi.org/10.1038/ngeo1797, 2013.

Schenk, F. and Zorita, E.: Reconstruction of high resolution atmospheric fields for Northern Europe using analog-upscaling, Climate of the Past, 8, 1681–1703, https://doi.org/10.5194/cp-8-1681-2012, 2012.

Schmidt, G. A.: Enhancing the relevance of palaeoclimate model/data comparisons for assessments of future climate change, J. Quaternary Sci., 25, 79–87, https://doi.org/10.1002/jqs.1314, 2010.

Schmidt, G. A., Jungclaus, J. H., Ammann, C. M., Bard, E., Braconnot, P., Crowley, T. J., Delaygue, G., Joos, F., Krivova, N. A., Muscheler, R., Otto-Bliesner, B. L., Pongratz, J., Shindell, D. T., Solanki, S. K., Steinhilber, F., and Vieira, L. E. A.: Climate forcing reconstructions for use in PMIP simulations of the Last Millennium (v1.1), Geoscientific Model Development, 5, 185–191, https://doi.org/10.5194/gmd-5-185-2012, 2012.

Schmidt, G. A., Annan, J. D., Bartlein, P. J., Cook, B. I., Guilyardi, E., Hargreaves, J. C., Harrison, S. P., Kageyama, M., LeGrande, A. N., Konecky, B., Lovejoy, S., Mann, M. E., Masson-Delmotte, V., Risi, C., Thompson, D., Timmermann, A., Tremblay, L. B., and Yiou, P.: Using palaeo-climate comparisons to constrain future projections in CMIP5, Climate of the Past, 10, 221–250, https://doi.org/10.5194/cp-10-221-2014, 2014.

Sigl, M., Winstrup, M., McConnell, J. R., Welten, K. C., Plunkett, G., Ludlow, F., Buntgen, U., Caffee, M., Chellman, N., Dahl-Jensen, D., Fischer, H., Kipfstuhl, S., Kostick, C., Maselli, O. J., Mekhaldi, F., Mulvaney, R., Muscheler, R., Pasteris, D. R., Pilcher, J. R., Salzer, M., Schupbach, S., Steffensen, J. P., Vinther, B. M., and Woodruff, T. E.: Timing and climate forcing of volcanic eruptions for the past 2,500 years, Nature, advance online publication, https://doi.org/10.1038/nature14565, http://dx.doi.org/10.1038/nature14565, 2015.

https://doi.org/10.5194/cp-2019-81
Preprint. Discussion started: 5 July 2019

Climate of the Past Discussions

Talento, S., Schneider, L., Werner, J., and Luterbacher, J.: Millennium-length precipitation reconstruction over south-eastern Asia: a pseudo-proxy approach, Earth System Dynamics, 10, 347–364, https://doi.org/10.5194/esd-10-347-2019, https://www.earth-syst-dynam.net/10/347/2019/, 2019.

Tolwinski-Ward, S. E., Anchukaitis, K. J., and Evans, M. N.: Bayesian parameter estimation and interpretation for an intermediate model of tree-ring width, Climate of the Past, 9, 1481–1493, https://doi.org/10.5194/cp-9-1481-2013, 2013.

Tolwinski-Ward, S. E., Tingley, M. P., Evans, M. N., Hughes, M. K., and Nychka, D. W.: Probabilistic reconstructions of local temperature and soil moisture from tree-ring data with potentially time-varying climatic response, Climate Dynamics, 44, 791–806, https://doi.org/10.1007/s00382-014-2139-z, 2015.

Trouet, V., Esper, J., Graham, N. E., Baker, A., Scourse, J. D., and Frank, D. C.: Persistent Positive North Atlantic Oscillation Mode Dominated the Medieval Climate Anomaly, Science, 324, 78–80, https://doi.org/10.1126/science.1166349, 2009.

University of East Anglia Climatic Research Unit, Harris, I., and Jones, P.: CRU TS4.01: Climatic Research Unit (CRU) Time-Series (TS) version 4.01 of high-resolution gridded data of month-by-month variation in climate (Jan. 1901- Dec. 2016), https://doi.org/10.5285/58a8802721c94c66ae45c3baa4d814d0, 2017.

Wilson, R., Anchukaitis, K., Briffa, K. R., Büntgen, U., Cook, E., D'Arrigo, R., Davi, N., Esper, J., Frank, D., Gunnarson, B., Hegerl, G., Helama, S., Klesse, S., Krusic, P. J., Linderholm, H. W., Myglan, V., Osborn, T. J., Rydval, M., Schneider, L., Schurer, A., Wiles, G., Zhang, P., and Zorita, E.: Last millennium northern hemisphere summer temperatures from tree rings: Part I: The long term context, Quaternary Science Reviews, 134, 1–18, https://doi.org/10.1016/j.quascirev.2015.12.005, 2016.

Zorita, E. and von Storch, H.: The Analog Method as a Simple Statistical Downscaling Technique: Comparison with More Complicated Methods, J. Climate, 12, 2474–2489, https://doi.org/10.1175/1520-0442(1999)012%3C2474:tamaas%3E2.0.co;2, 1999.