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Northern Hemisphere temperature reconstruction during the last millennium using multiple annual proxies

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ABSTRACT: Previous studies have either exclusively used annual tree-ring data or have combined tree-ring series with other, lower temporal resolution proxy series. Both approaches can lead to significant uncertainties, as tree-rings may underestimate the amplitude of past temperature variations, and the validity of non-annual records cannot be clearly assessed. In this study, we assembled 45 published Northern Hemisphere (NH) temperature proxy records covering the past millennium, each of which satisfied 3 essential criteria: the series must be of annual resolution, span at least a thousand years, and represent an explicit temperature signal. Suitable climate archives included ice cores, varved lake sediments, tree-rings and speleothems. We reconstructed the average annual land temperature series for the NH over the last millennium by applying 3 different reconstruction techniques: (1) principal components (PC) plus second-order autoregressive model (AR2), (2) composite plus scale (CPS) and (3) regularized errors-in-variables approach (EIV). Our reconstruction is in excellent agreement with 6 climate model simulations (including the first 5 models derived from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) and an earth system model of intermediate complexity (LOVECLIM), showing similar temperatures at multidecadal timescales; however, all simulations appear to underestimate the temperature during the Medieval Warm Period (MWP). A comparison with other NH reconstructions shows that our results are consistent with earlier studies. These results indicate that well-validated annual proxy series should be used to minimize proxy-based artifacts, and that these proxy series contain sufficient information to reconstruct the low-frequency climate variability over the past millennium.

KEY WORDS: Climate change · Global warming · Palaeoclimatology · Temperature reconstruction

1. INTRODUCTION

Assessing the rapid warming in the 20th century, which is unprecedented during the last millennium, continues to be one of the highest priorities for climatologists. One approach to this is to compare the current and past natural variations of climate as reconstructed from proxy data derived from natural archives (e.g. tree-rings, ice cores, speleothems and marine or lake sediments). Numerous proxy-based

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regional to global climate reconstructions have already been published (e.g. Jones et al. 1998, Mann et al. 1998, 1999, 2008, 2009, Crowley & Lowery 2000, Briffa et al. 2001, Esper et al. 2002a, Mann & Jones 2003, Cook et al. 2004a, Moberg et al. 2005, D'Arrigo et al. 2006, Osborn & Briffa 2006, Hegerl et al. 2007, Ammann & Wahl 2007, Kaufman et al. 2009, Ljungqvist 2010). However, the selection criteria for paleotemperature proxy series can significantly affect these large-scale composite temperature reconstructions (Küttel et al. 2007, Mann 2007, Jones et al. 2009, von Storch et al. 2009).

Two different approaches have usually been used to screen the predicted proxy records: either (1) only annual tree-ring data were used, or (2) tree-ring series were combined with non-annual records (see Table 1). The advantages of tree-ring data are that their chronologies have exact dating control and annual resolution, and their temperature signals are usually well understood and can be validated using meteorological data (Hughes 2011). In addition, tree-ring records are widespread for the Northen Hemisphere (NH). The problem with tree-ring series is that the low-frequency climate signal, longer than the age of the tree, is not well preserved, or, if present, it would need to be statistically extracted from the raw data (Cook et al. 1995, Briffa & Melvin 2011). Alternative proxy data (e.g. ice cores, speleothems, varved lake or marine sediments) are good proxies for the low-frequency temperature variability, and invariably come from regions where long tree-ring records are not available. However, the problem with those records is that most are not annually resolved and their quality is hard to assess because they usually cannot be validated using annual meteorological data. Therefore, both of these approaches have associated problems, as a pure tree-ring reconstruction may not reproduce the amplitude of past temperature changes correctly while non-annual data may introduce false or at least unvalidated information. New, non tree-ring records with annual resolution have recently been published. Thus, for this study, we assembled 45 proxy records including the tree-ring data and other proxy series with annual resolution to combine the advantages of all types of climate archives (Table 2), without their usual weaknesses.

Statistical techniques also have an important role in paleoclimate reconstruction (Christiansen 2011, McShane & Wyner 2011). Therefore, 3 different statistical techniques were used to reconstruct the annually resolved NH mean land temperature over the past 1000 yr, allowing us to analyze the effects of the different methods. Finally, we compared our reconstruction with other NH temperature reconstruction series and with 6 climate model simulations to assess its quality and reliability.

2. DATA AND METHODS

2.1. Instrumental and proxy data

Paleoclimate reconstructions may suffer from an aliasing effect when proxy data series with different temporal resolutions and different lengths are mixed (Mann et al. 2008). In this paper, criteria for the selection of the proxy records were very strict to minimize such effects. We only used proxy data series with annual resolution, which span >1000 yr, and represent an explicit temperature signal. For each research area, we considered only the newest data available and selected the data to ensure a uniform spatial distribution (Fig. 1, Table 2). Restricting data sets to those spanning >1000 yr was necessary to avoid heterogeneity in data set variance.

We started our proxy data collection using the large data set of climate records compiled by Mann et al. (2008), who collected 79 proxy records spanning >1000 yr to reconstruct NH temperatures. Of these series, 60 were not retained for this study, as they did not meet our very restrictive standards: e.g. some poor-quality data

Table 1. Number and types of data series used in multi-proxy Northern Hemisphere (NH) reconstructions (see Fig. 4). Only proxy series spanning at least 1000 yr were considered

	Type of proxy		Resolution		Total
	Dendro	Others	Annual	Non-annual	
This study	34	11	45	0	45
Ammann & Wahl (2007)	28	0	28	0	28
Christiansen & Ljungqvist (2012)	9	23	16	16	32
Crowley & Lowery (2000)	5	8	6	7	13
Esper et al. (2002a)	14	0	14	0	14
Hegerl et al. (2007)	11	3	0	14	14
Jones et al. (1998)	2	1	3	0	3
Ljungqvist (2010)	11	19	16	14	30
Mann et al. (1999)	28	0	28	0	28
Mann et al. (2008)	18	28	30	16	46
McShane & Wyner (2011)	62	33	77	18	95
Moberg et al. (2005)	7	11	8	10	18

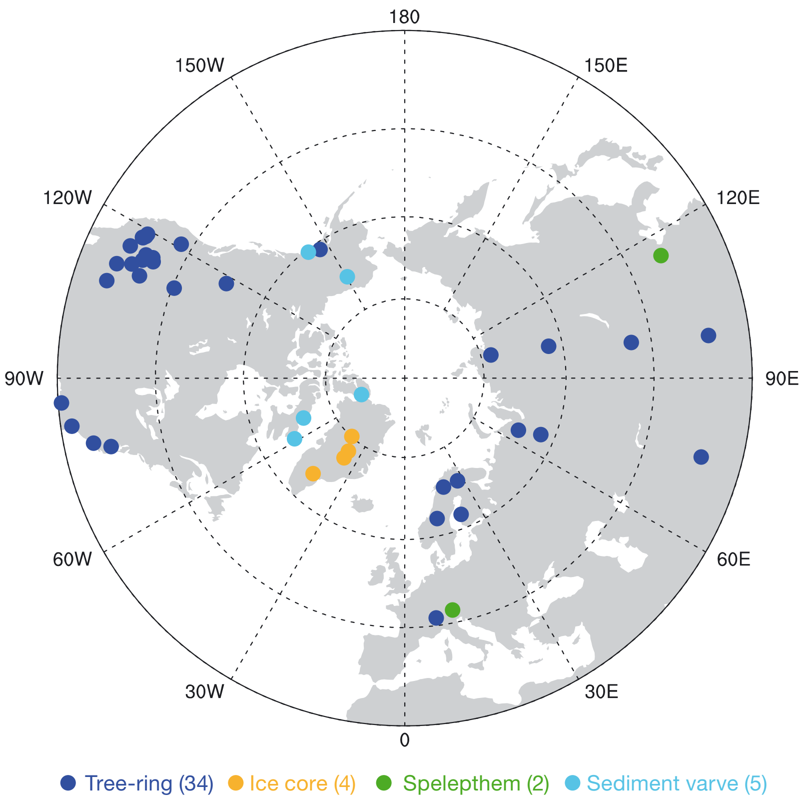


Fig. 1. Geographical distribution of the 45 records used in this study. Listed in Table 2

with a coarse resolution. Regional curve standardization (RCS) is an efficient method for preserving the low-frequency signal in the raw data (Briffa & Melvin 2011). We gave priority to the collection of RCS chronologies to better preserve the low-frequency signals.

Prior to a more in-depth examination of the series, we excluded 33 tree-ring records from the Mann et al. (2008) dataset, because they did not meet the minimal replication required for tree-ring series used in this study (5 independent contributing cores). Furthermore, 16 records with a non-annual resolution were excluded. For example, we did not use the lake sediment data derived from Lake Korttajärvi, as the sedimentation has been affected by human activity since the early 18th century (Tiljander 2005). Briffa et al.'s (1992) and Grudd's (2008) Fennoscandian tree-ring sampling areas are the same (Torneträsk, Northern Sweden), but the Grudd (2008) record was updated from AD 501 to 2004 using new samples from 35 relatively young trees. This new Torneträsk tree-ring maximum latewood density (MXD) record includes samples from a total of 100 trees and covers the period AD 441–2004. Therefore, we used the most up-to-date data from Grudd (2008). For Greenland, we used Vinther et al.'s (2010) annually resolved oxygen isotope record from ice cores. We did not use the older records published by Fisher et al. (1996) and Meese et al. (1994). The record compiled by Qian et al. (2003) represents centennial-scale dry–wet variations in East Asia, but not a specific temperature signal; it was thus not used in this study. Naurzbaev & Vaganov (2000) and Naurzbaev et al. (2002) both studied tree-rings in eastern Taimyr; the newer data by Naurzbaev et al. (2002) were used here. Also not considered for this study were the Scottish speleothem data published by Proctor et al. (2000, 2002) as the sensitivity of this archive to temperature is weak (strong negative correlation with precipitation). The latest update of the Yamal tree ring data (Briffa et al. 2008) used the RCS chronology and better reflects low frequency climate signals than former versions of the record (Briffa 2000, Hantemirov & Shiyatov 2002). The DYE-3 ice core data (Andersen et al. 2006) have been corrected for upstream depletion of $\delta^{18}O$ (Vinther et al. 2010). Consequently, only 19 of these 79 proxy series were in common with both the present and the Mann et al. (2008) reconstructions. We also collected 26 other records, resulting in a total of 45 series used for our temperature reconstruction (Table 2). All references for the 45 proxies come from 21 studies (see Table 2). Here, every series was required to exceed a 90% confidence level with either one of the 2 closest instrumental temperature grid points over the calibration interval to ensure that it had a significant statistical relationship with the local instrumental temperature signal.

Table 2 shows that the proxy records represent responses to temperature in different seasons, because of their variable local environments. For example, some tree-ring data strongly reflect the temperature of the growing season, while other tree-ring data also respond to mean annual temperature. The multidecadal variability of annual temperature and other season temperatures is usually synchronized (Jones et al. 2012). Thus, for consistency, all records were considered to approximately represent an entire year's temperature signal.

For calibration and verification purposes, we extracted the instrumental land-only NH temperature

Table 2. List of 45 annually resolved proxy records from the Northern Hemisphere (NH) used in this study. MXD: maximum latewood density; TRW: tree-ring width; RCS: regional curve standardization; Sp: speleothems; V: varved lake sediments; ITRDB: international tree-ring data bank; ND: not described; Δ: dating uncertainty

No.	Location	Latitude	Longitude	Proxy type	Season	Explained variance	Δ (yr)	Period covered	Reference
1	Torneträsk, Northern Sweden	68°21′N–68°31′N	19°45′E–19°80′E	MXD	Apr–Aug	0.4	±0	501–2004	Grudd (2008)
2	Swiss Alps	46°25′N	7°49′ E	MXD	Jun–Sep	0.49	±0	755–2004	Büntgen et al. (2006)
3	Canadian Rockies	52°N	117°W	MXD	May–Aug	0.53	±0	950–1994	Luckman & Wilson (2005)
4	Tibetan Plateau, China	35°50′N–36°30′N	97°40′E–98°20′E	TRW	Annual	0.48	±0	1–1999	Liu et al. (2009)
5	Northwest Karakorum, Mongolia	35°N–37°N	74°E–76° E	TRW	Annual	0.43	±0	618–1993	Esper et al. (2002b)
6	Polar Urals, Russia	66°52′N	65°38′E	TRW	May–Sep	ND	±0	778–1990	Esper et al. (2002a)
7	Jämtland, Sweden	63°10′N	12°25′E–13°35′E	TRW–RCS	Jun–Aug	0.40	±0	1–888, 908–1999	Linderholm & Gunnarson (2005)
8	Gulf of Alaska, USA	55°–62°N	131°–153°W	MXD	Jan–Sep	ND	±0	724–2000	D'Arrigo et al. (2006)
9	Taimyr peninsula, Russia	70°30′N–73°00′N	105°E	TRW–RCS	Jun–Aug	0.45	±0	1–1996	Naurzbaev et al. (2002)
10	Fennoscandia	62°5′N	22°5′E	TRW–RCS	Jun–Aug	0.19	±0	1–1997	Briffa et al. (2008)
11	Yamal, Russia	62°5′N	67°5′E	TRW–RCS	Jun–Jul	0.31	±0	1–1996	Briffa et al. (2008)
12	Avam–Taimyr, Russia	62°5′N	102°5′E	TRW–RCS	Jul	0.15	±0	1–2000	Briffa et al. (2008)
13	Campito mountain, USA	37°5′N	118°22′W	TRW	ND	ND	±0	626–1983	ITRDB, ca533
14	Sheep mountain, USA	37°37′N	118°22′W	TRW	ND	ND	±0	1–1990	ITRDB, ca534
15	Methuselah walk, USA	37°43′N	118°17′W	TRW	ND	ND	±0	1–1979	ITRDB, ca535
16	Spillway lake, USA	37°83′N	119°22′W	TRW	ND	ND	±0	800–1996	ITRDB, ca606
17	Glass Mountain, USA	37°75′N	118°68′W	TRW	ND	ND	±0	680–1998	ITRDB, ca633
18	Choctawhatchee River, USA	30°47′N	85°88′W	TRW	ND	ND	±0	899–1992	ITRDB, fl001
19	North Fork Ridge, USA	45°3′N	111°33′W	TRW	ND	ND	±0	500–1998	ITRDB, mt111
20	Black River, USA	34°32′N	78°22′W	TRW	ND	ND	±0	365–1985	ITRDB, nc008
21	El malpais national monument, USA	34°97′N	108°1′W	TRW	ND	ND	±0	1–1992	ITRDB, nm572
22	Pearl peak, USA	40°23′N	115°53′W	TRW	ND	ND	±0	320–1985	ITRDB, nv512
23	Pearl peak, USA	40°55′N	114°82′W	TRW	ND	ND	±0	302–1985	ITRDB, nv514
24	Indian garden, USA	39°08′N	115°43′W	TRW	ND	ND	±0	1–1980	ITRDB, nv515
25	Hill 10842, Nevada, USA	38°93′N	114°23′W	TRW	ND	ND	±0	1–1984	ITRDB, nv516
26	Springs mountains lower, Nevada, USA	36°32′N	115°7′W	TRW	ND	ND	±0	320–1984	ITRDB, nv517
27	Table Rock/Arrow Gap, USA	43°18′N	120°9′W	TRW	ND	ND	±0	530–1996	ITRDB, or062
28	Wild horse ridge, USA	39°42′N	111°07′W	TRW	ND	ND	±0	286–1985	ITRDB, ut508
29	Mammoth creek, USA	37°65′N	112°67′W	TRW	ND	ND	±0	1–1989	ITRDB, ut509
30	San Francisco peaks, USA	35°5′N	111°67′W	TRW	ND	ND	±0	548–1983	ITRDB, az510
31	Altamaha river, USA	31°62′N	81°8′W	TRW	ND	ND	±0	929–1985	ITRDB, ga002

Table 2 (continued)

No.	Location	Latitude	Longitude	Proxy type	Season	Explained variance	Δ (yr)	Period covered	Reference
32	Blackwater river, USA	36°78'N	76°88'W	TRW	ND	ND	±0	932–1985	ITRDB, va021
33	Laanila, northern Finland	68°28'N–68°31'N	27°16'E–27°24'E	Height-increment record	Jun–Aug	0.36	±0	745–2000	Lindholm et al. (2011)
34	Solongotyn Davaa, Mongolia	48°3'N	98°93'E	TRW	Jul	0.33	±0	264–1998	D'Arrigo et al. (2001)
35	GRIP, Greenland	72°58'N	37°64'W	Ice core $\delta^{18}O$	May–Oct	ND	±0	551–1979	Vinther et al. (2010)
36	DYE-3, Greenland	65°18'N	43°83'W	Ice core $\delta^{18}O$	May–Oct	ND	±0	551–1978	Vinther et al. (2010)
37	Crete, Greenland	71°12'N	37°32'W	Ice core $\delta^{18}O$	May–Oct	ND	±0	552–1973	Vinther et al. (2010)
38	NGRIP, Greenland	75°10'N	42°32'W	Ice core $\delta^{18}O$	Annual	ND	±21	5–2000	Vinther et al. (2006)
39	Beijing, China	39°54'N	116°23'E	Sp	May–Aug	0.3	±5	1–1986	Tan et al. (2003)
40	Central Alps	47°05'N	11°40'E	Sp	Annual	ND	<4	1–1935	Mangini et al. (2005)
41	Canadian Arctic	81°21'N	69°32'W	V	Jul	ND	ND	1–1969, 1990–2000	Cook et al. (2009)
42	Canadian Arctic	69°52'N	68°5'W	V	Jul–Sep	0.20	ND	971–2000	Thomas & Briner (2009)
43	Southern Alaska, USA	60°47'N	142°57'W	V	May–Jun	0.05	±32	442–1998	Loso (2009)
44	Canadian Arctic	66°4'N	61°21'W	V	Jun–Aug	0.30	±80	752–1992	Moore et al. (2001)
45	Alaska, USA	68°09'N	150°47'W	V	Jun–Aug	0.10	±45	9–2000	Bird et al. (2009)

data for the period AD 1850 to 2006 from the University of East Anglia (Climatic Research Unit [CRU], Norwich, UK; www.cru.uea.ac.uk/cru/data/temperature) instrumental surface-air temperature dataset (CRUTEM3v) (Brohan et al. 2006).

2.2. Statistical methods

Three different reconstruction methodologies were used to reconstruct NH temperatures during the last 1000 yr: multivariate principal component regression (PCR), composite-plus-scaling (CPS) and the regularized errors-in-variables approach (EIV).

Principal components (PC) regression has been used in climate reconstruction research for many years (Cook et al. 1994, 2004b, Luterbacher et al. 2004, Riedwyl et al. 2009). It is well known that there is no single objective way by which to select the PCs (Wilks 2006, McShane & Wyner 2011). According to the cross-validated root mean square error (RMSE) results, the first 10 PCs of the proxy record dataset and a second-order autoregressive (AR2) model were retained (McShane & Wyner 2011). The AR2 can be used to statistically and optimally reduce the uncertainty of the regression equation errors (McShane & Wyner 2011). The model was fitted to the period AD 1850–1998 and used to reconstruct the period AD 998–1849. A Bayesian algorithm was used to estimate parameter uncertainty and residual variance using McShane & Wyner's (2011) method, yielding a much wider standard error because of noise in the proxy data and uncertainty in the relationship between the proxy data and instrumental data (McShane & Wyner 2011). The likelihood is given by McShane & Wyner (2011):

$$T_t = \beta_0 + \sum_{i=1}^{10} \beta_i (\mathrm{PC})_{t,i} + \beta_{11} T_{t+1} + \beta_{12} T_{t+2} + \varepsilon_t \qquad (1)$$

where T_t represents the CRU NH annual land temperature in year t and $(\mathrm{PC})_{t,i}$ is the value of principal component i in year t. The innovations ε_t are assumed to be independent and identically distributed normal draws, $\varepsilon_t \in N(0, \sigma^2)$. All parameters are defined according to McShane & Wyner (2011), and the computational code for this method is available in their supplement.

Northern Hemisphere annual mean land temperatures were reconstructed by an AR2 model with the first 10 PCs of the dataset. The posterior was estimated using Just Another Gibbs Sampler (JAGS) (Plummer 2003) and Markov Chain Monte Carlo (MCMC) method over the calibration period (AD

1850–1998). The 95% confidence interval was calculated after 100 iterations.

PCR using simple linear regression of PCs of the proxy network and instrumental data suffers from known biases, including the underestimation of variance (von Storch et al. 2004, Hegerl et al. 2006, Neukom et al. 2011). To avoid this potential loss of variance, we also used CPS by matching the variance of the composited predictor data against the predictand in the calibration period (Jones et al. 1998, Esper et al. 2005). This is sometimes called the composite matching variance method (von Storch et al. 2009). Moreover, EIV with truncated total least squares was used to avoid overfitting in the regressions (Schneider 2001, Rutherford et al. 2005, Mann 2007, Mann et al. 2008, 2009, Riedwyl et al. 2008, 2009, Neukom et al. 2011). For a general comparison and description of the 3 approaches we refer to McShane & Wyner (2011) and corresponding discussion articles (Schmidt et al. 2011, Smerdon 2011, Tingley 2011). The procedures for all the methods are available in the supplements to original papers in the references.

2.3. Climate models

In order to assess whether our reconstructions are consistent with the model physics, a comparison is carried out with the climate of the last millennium assessed by the 6 following models: MPI-ESM-P (Jungclaus et al. 2010), CCSM4 (Gent et al. 2011), GISS-E2-R (Schmidt et al. 2006), FGOALS-g1 (Zhou et al. 2008), BCC-CSM1.1 (Wu et al. 2010) and LOVECLIM1.2 (Goosse et al. 2010). These results are the stacked reconstruction of the Paleo Modelling Intercomparison Project Phase 3 (PMIP3) (Schmidt et al. 2012) last millennium simulation and the CMIP5 historical run. The results for these two projects are available via the Earth System Grid Federation portal (http://pcmdi9.llnl.gov/esgf-web-fe/) except for LOVECLIM, available at http://www.climate.be/lm/.

3. RESULTS AND DISCUSSION

Northern Hemisphere annual mean land temperatures anomalies (with respect to AD 1961 to 1990) over the last 1000 yr, reconstructed with 3 statistical approaches (PC10+AR2, CPS and EIV) are shown in Fig. 2a. The model was fitted to the period AD 1850–1998 and reconstructed for AD 998–1849. A Medieval Warm Period (MWP) prior to AD 1100, a colder Little Ice Age type event (LIA; AD ~1550–1750) and the 20th century warming are visible in the NH. The period of the LIA agrees with the reconstructions of Moberg et al. (2005) and Mann et al. (2008) that reveal cooler conditions in the NH during the intervals AD 1500–1600, 1400–1700 and 1500–1800. The most recent decades (AD 1920–1998) were clearly warmer than any period of the past 1000 yr. These posterior probabilities clearly support the assessments by Mann et al. (2008) and the Intergovernmental Panel for Climate Change (IPCC) AR4 (Jansen et al. 2007) stating that the current warming is unprecedented during the past 1000 yr. About 64 yr quasi-cycles are identified in the 3 reconstructions by wavelet analysis (not shown), which are not statistically significant. Fig. 2b compares the reconstructed results with the instrumental data since 1840. Note that the value of the EIV reconstruction is the same as the filtered instrumental data since 1850, because the EIV method is an algorithm for the imputation of missing values in incomplete datasets. Fig. 2b shows that the PC1+AR2 result is closer to the filtered instrumental data (i.e. the EIV result) than the CPS result. Fig. 2c shows results reconstructed using the no-dendro dataset, and Fig. 2d shows the dendro results. 'no dendro' means the results obtained using the proxy datasets after excluding the tree-ring records, and 'dendro' means the results reconstructed only using tree-ring data. Fig. 2c,d indicates that the reconstruction technique has an important effect on the reconstruction results, especially for the very small number of proxy data used in Fig. 2c. There are only 11 proxy records in the 'no-dendro' case. Overall, the results in this study are all very similar, with no distinct differences in the cold/warm phases of the reconstruction results at multidecadal timescales. However, the means and amplitudes of the 3 results are distinctly different due to the different regression equations (i.e. the transfer functions) of the 3 techniques. For example, Fig. 2b reveals that the composited proxy records obtained using PC10+AR2 and CPS are distinctly different after AD 1840. Thus, the backcasted results from these 2 methods would be inconsistent. The values of the instrumental data and proxy records during the calibration period should include their maximum and minimum values to render a stable regression equation (Fritts 1976). However, this is very difficult for paleoclimate reconstructions with short instrumental data series. The EIV result is distinctly higher than the others before AD 1700, especially during the MWP. Similar results were also found in other reconstructions. Mann et al. (2008) showed that the EIV

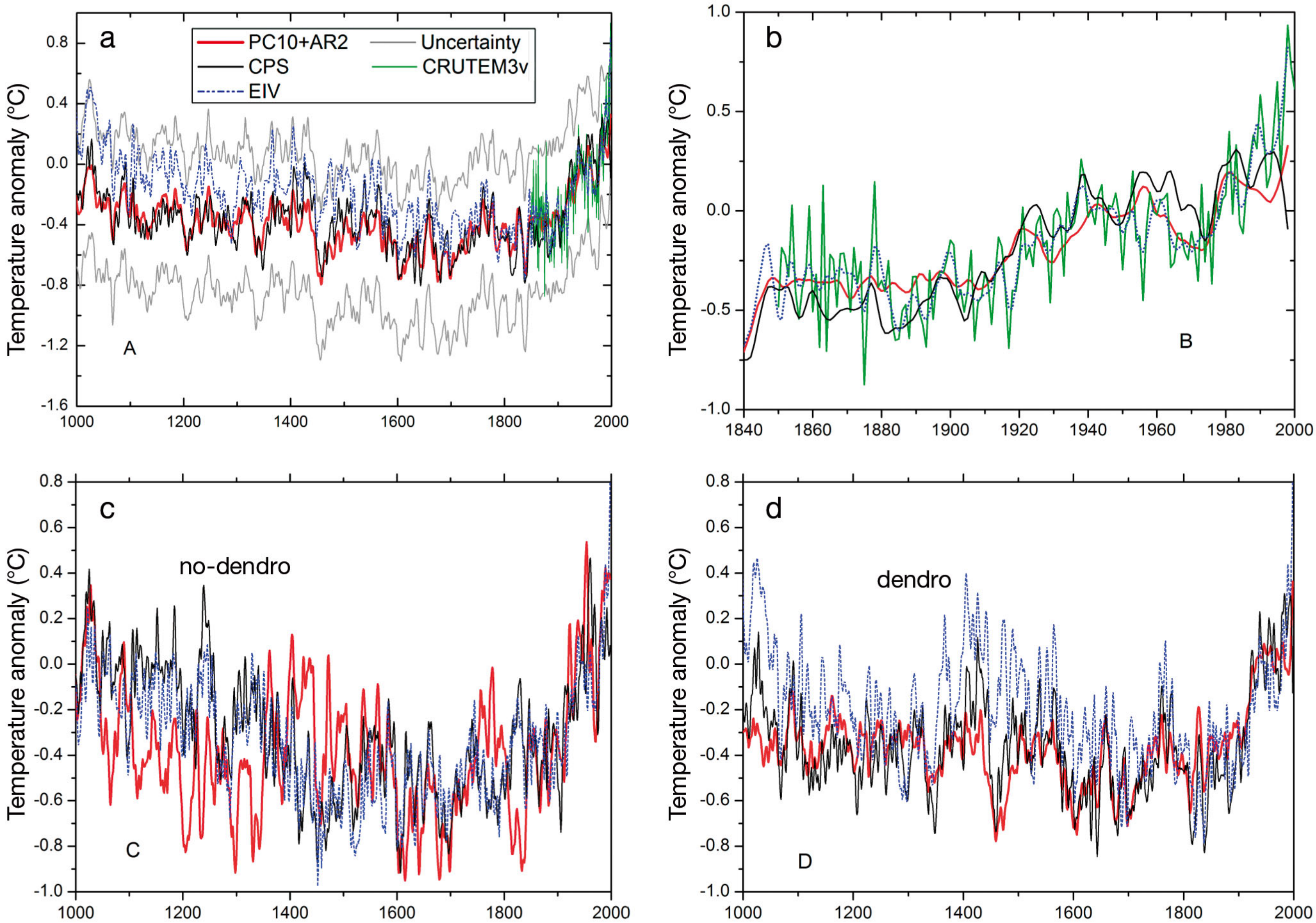
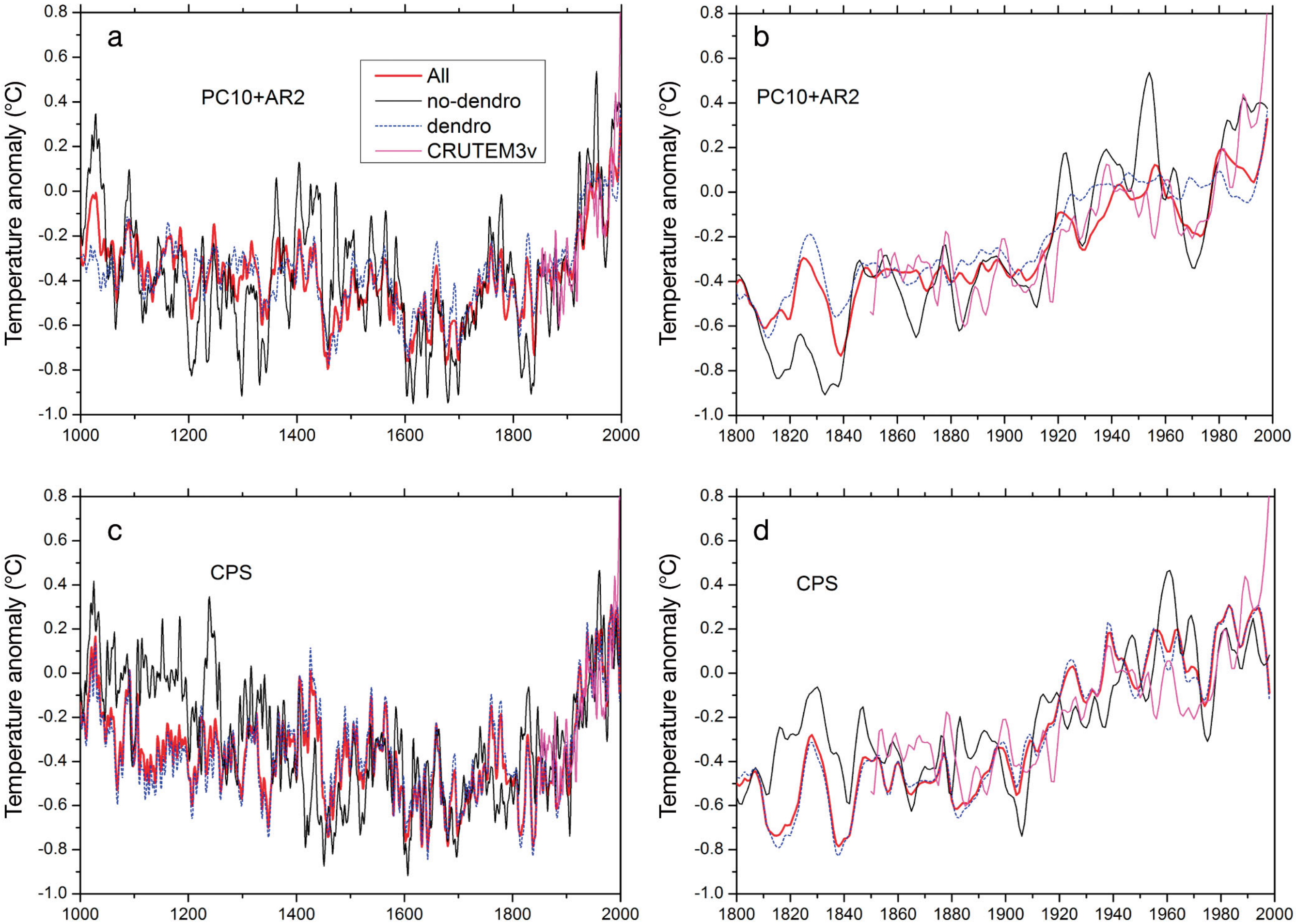


Fig. 2. Northern Hemisphere (NH) land temperature anomalies (with respect to AD 1961–1990) over the last 1000 yr reconstructed with PC10+AR2 (red solid line), CPS (black solid line) and EIV (blue dashed line). The 3 reconstruction results were smoothed by the loess method (span: 0.01). All models were fitted to the period AD 1850–1998 and reconstructed for AD 998–1849. Reconstructions for (a) AD 1000–2000 and (b) 1840–2000. Olive line: instrumental CRU NH annual mean land temperature. Gray lines: uncertainty associated with the PC10+AR2 reconstruction. Reconstructions results using (c) no-dendro data (i.e. using other types of proxy records, excluding tree-ring records), and (d) tree-ring records (dendro). Methods: 10 principal components plus second-order autoregressive model (PC10+AR2), composite plus scale (CPS) and regularized errors-in-variables approach (EIV)

method produces significantly higher temperatures in the 11th century warm period than the CPS approach. Also, Riedwyl et al. (2009) showed that PC regression underestimates the amplitude of past temperature variability, and the regularized expectation maximization (RegEM) method overestimates the temperature amplitude. This indicates that the choice of the reconstruction technique has an influence on the final paleoclimate reconstruction.

Fig. 3 compares NH land temperature anomalies (with respect to AD 1961–1990) over the last 1000 yr obtained with and without tree-ring records. 'All' means that all 45 proxy records were used to reconstruct the results. All results were smoothed by the loess method (span: 0.01), fitted for AD 1850–1998 and reconstructed for AD 998–1849. Fig. 3a shows the PC10+AR2 results for the last 1000 yr, and Fig. 3b the same results for AD 1800–1998. Fig. 3c shows the CPS results over the last 1000 yr, and Fig. 3d the same results for AD 1800–1998. For the PC10+AR2 and CPS results, the amplitudes of the 'non-dendro' results are distinctly larger than those of the 'dendro' and 'All' results. This is consistent with the 'non-dendro' records retaining more information on the low-frequency variability. For the EIV results in Fig. 3e, all 3 results have large amplitudes; however, these results need to be further verified. It can be argued that even though the improvements and development of reconstruction techniques are very important, the most fundamental factor affecting climate reconstruction is still the quantity and quality of the input proxy data.



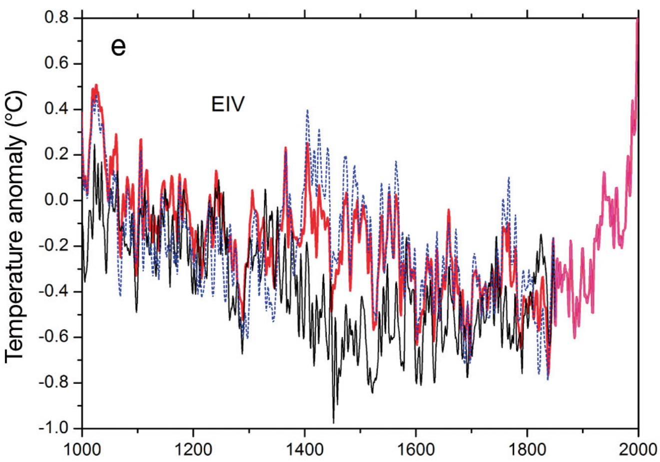


Fig. 3. Comparison of Northern Hemisphere land temperature reconstructions (with respect to AD 1961–1990) over the last 1000 yr with (dendro) and without (no-dendro) tree-ring records. All models were fitted in the period AD 1850–1998 and reconstructed for AD 998–1849. 'All': results using 45 proxy records. Results for PC10+AR2 (a) over the last 1000 yr and (b) for AD 1800–1998. CPS results (c) over the last 1000 yr and (d) for AD 1800–1998. (e) EIV results over the last 1000 yr. All series were smoothed by the loess method (span: 0.01)

Fig. 4 compares our reconstruction with other reconstructions, with 0.05 filtered values for AD 1001–1960. To facilitate comparison, every series was firstly expressed as anomalies from AD 1850–1960, and was then variance matched using the instrumental data from AD 1850–1960. Ljungqvist's (2010) result was interpolated to annual resolution and was then filtered by a 0.05 span.' Mann et al. (2008) CPS' is for the NH reconstruction result based on the CPS method, while the 'Mann et al. (2008) EIV' is for that based on the EIV method. Ammann & Wahl's (2007) curve was established by reinterpreting Mann et

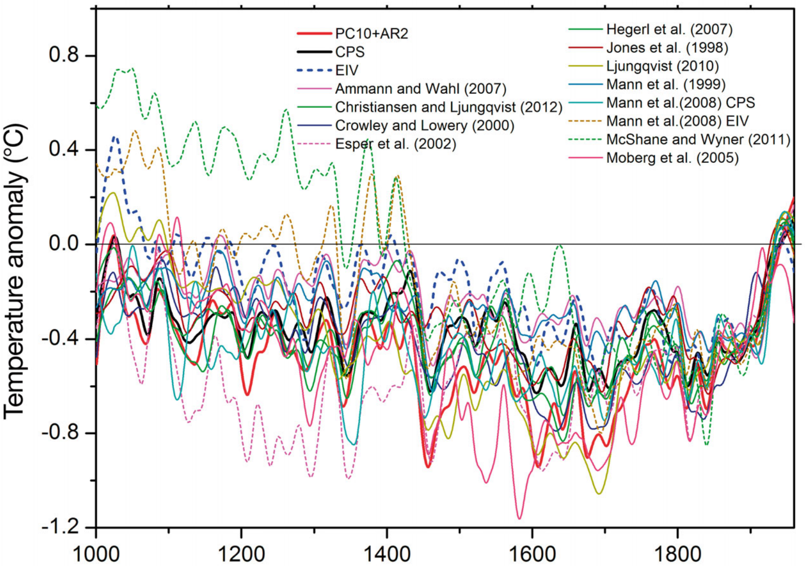


Fig. 4. Comparison of different Northern Hemisphere (NH) temperature reconstructions. All series were variance matched with the overlapping segment of CRUTEM3v instrumental NH land temperature record for 1850–1960. All reconstructions were filtered by the loess method (span: 0.05). Reconstructions: PC10+AR2 (red solid line), CPS (black solid line) and EIV (blue dashed line). Base period: AD 1001–1960

al. (1999), and shows little difference. These results show that our models are very similar to those from other studies in terms of the multi-decadal variability. In particular, the value of temperature variability in PC10+AR2 and CPS reconstructions during the MWP is generally lower than in some new reconstructions (Mann et al. 2008 EIV, Ljungqvist 2010, McShane & Wyner 2011), but the EIV result is equivalent to those of Mann et al. (2008) CPS and Ljungqvist (2010). Table 3 shows 100 yr arithmetic means of the temperature reconstructions depicted in Fig. 4. All 3 reconstructions are very similar to the reconstructions of Christiansen & Ljungqvist (2012), Crowley & Lowery (2000), Hegerl et al. (2007), Jones et al. (1998), Ljungqvist (2010) and Mann et al. (2008) CPS, which indicate lower temperatures than other reconstructions in the 11th century, when most reconstructions indicate cooler conditions than in the 20th century, except for Mann et al. (2008) EIV, Ljungqvist (2010) and McShane & Wyner (2011). The coldest century of our reconstruction was the 17th century. This result is similar to reconstructions by Christiansen & Ljungqvist (2012), Crowley & Lowery (2000), Hegerl et al. (2007), Jones et al. (1998), Mann et al. (2008) EIV and Moberg et al. (2005). Different results were found by

Table 3. Centennial Northern Hemisphere mean temperatures. Mean base period: AD 1900–1960 in the 20th century; PC10+AR2: 10 principal components plus the second order auto-regressive model; CPS: composite plus scale; EIV: errors-in-variables approach

Century	PC10+AR2	CPS	EIV	Ammann & Wahl (2007)	Christiansen & Ljungqvist (2012)	Crowley & Lowery (2000)	Esper et al. (2002a)	Hegerl et al. (2007)	Jones et al. (1998)	Ljungqvist (2010)	Mann et al. (1999)	Mann et al. (2008) CPS	Mann et al. (2008) EIV	McShane & Wyner (2011)	Moberg et al. (2005)
11th	−0.23	−0.18	0.13	−0.12	−0.15	−0.21	−0.25	−0.22	−0.15	0.09	−0.16	−0.22	0.34	0.62	−0.10
12th	−0.36	−0.34	−0.04	−0.12	−0.33	−0.23	−0.61	−0.40	−0.26	−0.18	−0.17	−0.44	−0.05	0.42	−0.18
13th	−0.46	−0.36	−0.19	−0.18	−0.41	−0.34	−0.85	−0.43	−0.29	−0.22	−0.22	−0.35	0.01	0.36	−0.43
14th	−0.43	−0.36	−0.13	−0.16	−0.39	−0.34	−0.70	−0.41	−0.23	−0.43	−0.20	−0.52	−0.05	0.19	−0.45
15th	−0.59	−0.34	−0.13	−0.22	−0.41	−0.45	−0.61	−0.34	−0.31	−0.63	−0.36	−0.48	−0.17	−0.17	−0.52
16th	−0.56	−0.36	−0.23	−0.28	−0.42	−0.49	−0.46	−0.46	−0.42	−0.63	−0.29	−0.54	−0.41	−0.28	−0.89
17th	−0.77	−0.53	−0.39	−0.32	−0.56	−0.72	−0.76	−0.68	−0.52	−0.90	−0.35	−0.59	−0.52	−0.33	−0.85
18th	−0.58	−0.43	−0.36	−0.28	−0.46	−0.55	−0.53	−0.41	−0.31	−0.57	−0.29	−0.51	−0.45	−0.42	−0.67
19th	−0.52	−0.49	−0.41	−0.37	−0.49	−0.57	−0.54	−0.51	−0.49	−0.49	−0.39	−0.47	−0.46	−0.54	−0.56
20th	−0.12	−0.10	−0.16	−0.16	−0.12	−0.07	−0.12	−0.09	−0.07	−0.11	−0.15	−0.15	−0.12	−0.12	−0.14

Table 4. Correlation coefficient matrix between all Northern Hemisphere temperature series over the period AD 1001–1960

Correlation coefficient	PC10+AR2	CPS	EIV	Ammann & Wahl (2007)	Christiansen & Ljungqvist (2012)	Crowley & Lowery (2000)	Esper et al. (2002a)	Hegerl et al. (2007)	Jones et al. (1998)	Ljungqvist (2010)	Mann et al. (1999)	Mann et al. (2008) CPS	Mann et al. (2008) EIV	McShane & Wyner (2011)	Moberg et al. (2005)
PC10+AR2	1.00	0.90	0.72	0.70	0.88	0.85	0.64	0.79	0.74	0.85	0.75	0.65	0.71	0.59	0.77
CPS	0.90	1.00	0.76	0.74	0.91	0.79	0.72	0.87	0.74	0.72	0.74	0.65	0.70	0.52	0.67
EIV	0.72	0.76	1.00	0.65	0.77	0.70	0.38	0.62	0.65	0.73	0.59	0.48	0.79	0.79	0.70
Ammann & Wahl (2007)	0.70	0.74	0.65	1.00	0.69	0.71	0.35	0.69	0.73	0.63	0.93	0.57	0.76	0.67	0.56
Christiansen & Ljungqvist (2012)	0.88	0.91	0.77	0.69	1.00	0.81	0.71	0.87	0.74	0.82	0.71	0.72	0.73	0.58	0.73
Crowley & Lowery (2000)	0.85	0.79	0.70	0.71	0.81	1.00	0.50	0.78	0.80	0.85	0.72	0.63	0.76	0.68	0.80
Esper et al. (2002a)	0.64	0.72	0.38	0.35	0.71	0.50	1.00	0.68	0.45	0.45	0.42	0.48	0.28	0.05	0.43
Hegerl et al. (2007)	0.79	0.87	0.62	0.69	0.87	0.78	0.68	1.00	0.77	0.70	0.66	0.71	0.67	0.42	0.68
Jones et al. (1998)	0.74	0.74	0.65	0.73	0.74	0.80	0.45	0.77	1.00	0.73	0.73	0.61	0.70	0.57	0.68
Ljungqvist (2010)	0.85	0.72	0.73	0.63	0.82	0.85	0.45	0.70	0.73	1.00	0.68	0.71	0.82	0.76	0.84
Mann et al. (1999)	0.75	0.74	0.59	0.93	0.71	0.72	0.42	0.66	0.73	0.68	1.00	0.58	0.70	0.64	0.55
Mann et al. (2008) CPS	0.65	0.65	0.48	0.57	0.72	0.63	0.48	0.71	0.61	0.71	0.58	1.00	0.71	0.50	0.58
Mann et al. (2008) EIV	0.71	0.70	0.79	0.76	0.73	0.76	0.28	0.67	0.70	0.82	0.70	0.71	1.00	0.89	0.74
McShane & Wyner (2011)	0.59	0.52	0.79	0.67	0.58	0.68	0.05	0.42	0.57	0.76	0.64	0.50	0.89	1.00	0.67
Moberg et al. (2005)	0.77	0.67	0.70	0.56	0.73	0.80	0.43	0.68	0.68	0.84	0.55	0.58	0.74	0.67	1.00

Mann et al. (2008) CPS and Moberg et al. (2005), who found that the coldest episode occurred in the 16th century, and by Ammann & Wahl (2007), Mann et al. (1999) and McShane & Wyner (2011) who found the coldest interval in the 19th century. In conclusion, it appears that for the NH, the LIA maximum cooling occurred mainly during the 16th and 17th centuries. Table 4 is a correlation matrix between all the series over the common period 1001–1960. The correlation coefficients between the PC10+AR2 reconstructions and other studies are all >0.7, except for Esper et al. (2002a), Mann et al. (2008) CPS and McShane & Wyner (2011). The CPS and EIV results follow a similar pattern. These findings further illustrate that our reconstructions are well correlated with others with respect to the multi-decadal variability.

We compared our results with 6 climate model simulations over the past millennium to assess the agreement between our reconstruction and the climate physics (Fig. 5). Fig. 5 shows that the reconstructed multi-decadal variability is in very good agreement with the model results over the pre-industrial period. In addition, the amplitudes of the

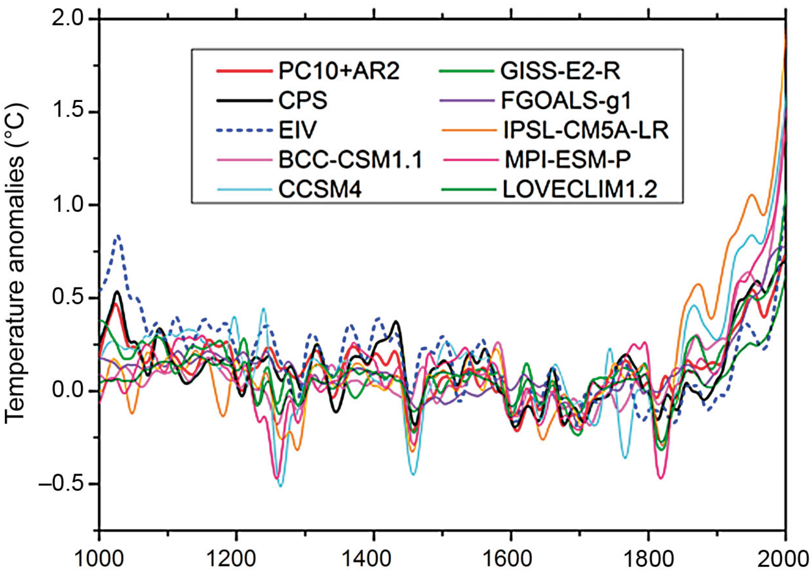


Fig. 5. Annual Northern Hemisphere temperature anomalies (with respect to AD1500–1850) smoothed with a loess filter (span: 0.05) for PC10+AR2, CPS and EIV reconstructions and 6 climate model simulations: BCC-CSM1.1, CCSM4, GISS-E2-R, FGOALS-g1, IPSL-CM5A-LR, MPI-ESM-P and LOVECLIM1.2. Base period: AD 1000–2000

models are very similar to the reconstruction except during the MWP. All curves display a general long-term cooling trend from the beginning of the millennium until AD ~1849. Some particularly cold periods are also well represented both in the simulations and in the reconstruction, such as AD ~1452–1453 and in the 17th century. However, the cooling simulated after the AD 1258 and Tambora eruptions (AD 1815) is much larger than in the reconstruction. Our results indicate that while some volcanic eruptions were captured by our reconstructions, others were less distinct. The reason is that there are some uncertainties both in the simulation and in the reconstruction (Anchukaitis et al. 2012, Mann et al. 2012). However, the paleoclimate reconstruction, to a certain extent, can capture the volcanic cooling and provides a unique opportunity to test model simulations (Braconnot et al. 2012). It is worth noting that all model simulations underestimated the temperature of the MWP. The causes of those discrepancies between the reconstruction and simulated results are difficult to assess, but we emphasize that both approaches yield the same overall pattern for the past millennium, despite their respective errors.

4. CONCLUSIONS

We selected 45 paleotemperature proxy records on the basis of 3 criteria (annual resolution, >1 millennium in length, and representing an explicit temperature signal) in order to minimize artifacts due to (1) combination of time series of different lengths or resolution and (2) non-climatic artifacts. Using these records, NH temperature over the last millennium was reconstructed using 3 different reconstruction techniques: principal component regression (PC10+AR2), composite plus scale (CPS) and the regularized errors-in-variables approach (EIV). The high quality of our reconstructions is demonstrated by the very good agreement with 6 independent climate model simulations; however, our reconstructions yielded distinctly warmer temperatures than those in all simulations during the MWP, and while our reconstructions captured the largest tropical volcanic eruption cooling event with a magnitude equivalent to that in the simulations, the other eruption cooling events were not distinct. There were notable differences between the temperature reconstructions derived from different reconstruction methods, proving that the improvement and development of reconstruction techniques is of importance for current paleoclimate reconstructions. Our results also indicate that the amplitude of the reconstruction based only on the annually resolved dataset is equivalent to that of other reconstructions with non-annually resolved datasets. Thus, we advise the exclusive use of annually resolved proxy data which represent clearly a temperature, and which have been validated using meteorological data.

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