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Supplement of

Reconstructing Late Holocene North Atlantic atmospheric circulation changes using functional paleoclimate networks

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S1 Possible impacts on human societies

As mentioned in Sec. 5.3 of the main paper, it can be expected that at longer time scales, the alternation between different phases of the NAO has had a considerable impact on human societies via modifications of temperature and precipitation patterns and their resulting consequences for natural and agricultural ecosystems (Hurrell et al., 2003; Hurrell and Deser, 2010, and references therein). In the following, we discuss possible implications of our qualitative reconstruction of the NAO phase in the context of European history during the Common Era. Since the climatic influence of the NAO differs among different parts of Europe, we restrict this discussion to two key regions, the Western Roman Empire and Norse colonies in the North Atlantic. Prior to presenting some further thoughts on corresponding relationships, we emphasize that one has to keep in mind, that climatic conditions have almost never been the sole reason for societal changes. However, they can be either beneficial or disadvantageous, also depending on how vulnerable a society is to environmental disruptions (Diaz and Trouet, 2014; Weiss and Bradley, 2001; Diamond, 2005). Because of the complex interrelationship between human societies and environmental and climatic factors (Engler, 2012; Engler and Werner, 2015), discussions about any possible causal links would in general be highly speculative, so that we explicitly refrain from making any corresponding claims.

Our qualitative NAO reconstruction describes a prevalent negative NAO phase with shorter interruptions by positive phases until about 450 CE. In the Western Mediterranean, such a climatic setting commonly corresponds to milder and wetter winters (Hurrell et al., 2003). This expectation is in line with previous descriptions of this period as warm (Luterbacher et al., 2016) and humid (García et al., 2007; Martín-Chivelet et al., 2011; Desprat et al., 2003), even though there is considerable disagreement about the exact timing of the termination of this phase among different paleoclimate archives. The aforementioned conditions might have generally been beneficial for the Western Roman Empire (McCormick et al., 2012). In turn, decreasing temperatures, together with more frequent droughts following the RWP might have progressively added stress to societies in the Western Mediterranean, which had already been weakened by internal conflicts, plagues, invasions and other factors at this time (McCormick et al., 2012; Diaz and Trouet, 2014). López-Moreno and Vicente-Serrano (2008) describe that a corresponding effect could have played a key role not only in the Western Mediterranean, but also in the Northern Balkan region. Thus, during the prolonged negative phase in the 4$^{\text{th}}$ and 5$^{\text{th}}$ century CE, these regions received higher precipitation and might thus have been a target for invading Huns, who were possibly aiming to escape drought conditions in Central Asia (McCormick et al., 2012) triggering the mass migration of the Late Antique (Halsall, 2007).

Patterson et al. (2010) discussed the impact of North Atlantic seasonality on Norse colonies based upon δ^{18}O values of near-shore mollusks from Iceland, which trace changes in the ocean circulation potentially accompanied by certain preferred NAO patterns. Specifically, they reported cold periods around 410 CE and between 1380 and 1420 CE, while warm temperatures are noted from 230 BCE to 140 CE and around 600 to 1000 CE. The latter is consistent with findings by Werner et al. (2017), who date the maximum of the MCA in the Arctic to the period between about 960 and 1060 CE, which is in line with our qualitative NAO reconstruction. A positive NAO phase during the second half of the first millennium would have lead to generally warmer temperatures and less sea ice and would thus have been favorable to marine ecosystems in the region (Hurrell et al., 2003). While a positive NAO phase could have been beneficial for settlement on, and sustained population of Iceland, it was also associated with enhanced storm activity and increased wave heights in the North Atlantic (Serreze et al., 1997; Bader et al., 2011), rendering the sailing conditions more difficult. The first evidence of settlements on Iceland dates back to around 870 CE, a time at which our reconstruction indicates a short period of negative NAO phase. This implies, that while the overall positive NAO phase was helpful for establishing these settlements, short negative NAO phases were supportive for longer expeditions across the North Atlantic. Settlement on Greenland follows a similar pattern, being established during the late 9$^{\text{th}}$ century, which again corresponds to a period of probably negative NAO phase. The situation differs from those in Iceland in that negative NAO phases would be accompanied by warmer temperatures in Greenland. Thus, the negative NAO phases during the MCA could have been beneficial for settlement in Southern Greenland. In turn, during the 14$^{\text{th}}$ century – a phase of prolonged positive NAO and, thus, lower temperatures – most of the Norse colonies on Greenland were abandoned, possibly affected by the associated environmental changes (Diamond, 2005).

In summary, some key periods of the history of those parts of Europe that are most strongly exposed to long-term variations of North Atlantic climate appear closely related with environmental changes that are consistent with our qualitative NAO reconstruction, providing additional evidence for the general validity of the obtained long-term patterns.

S2 Additional tables and figures

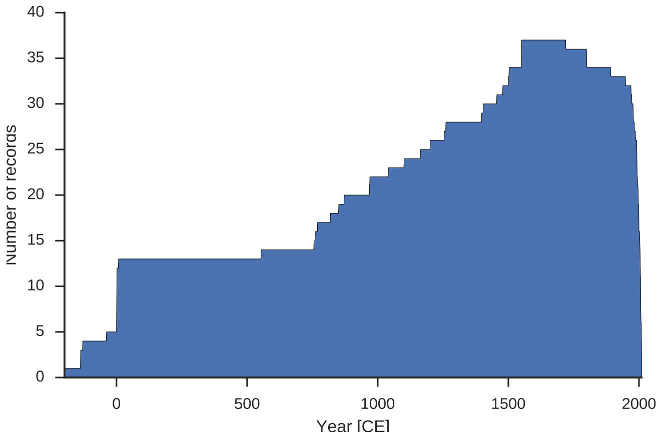
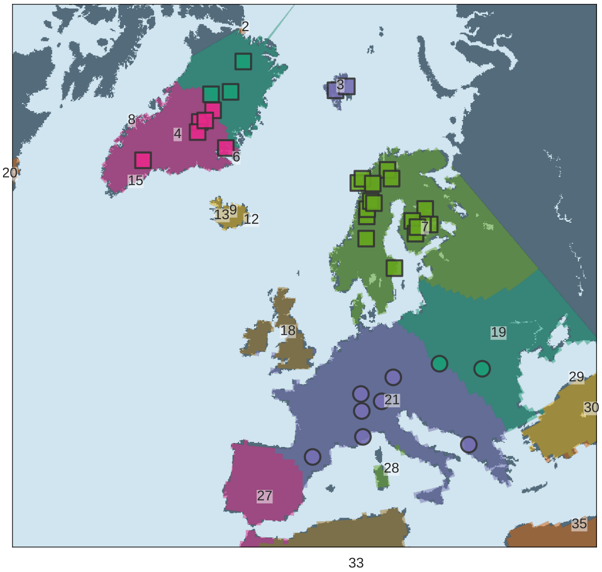
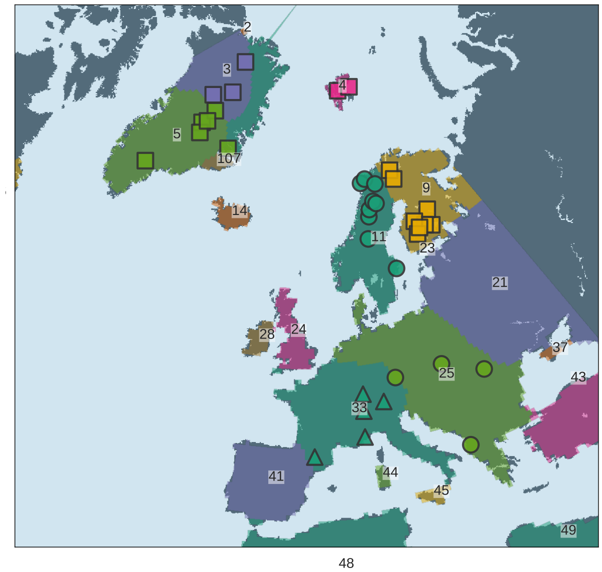


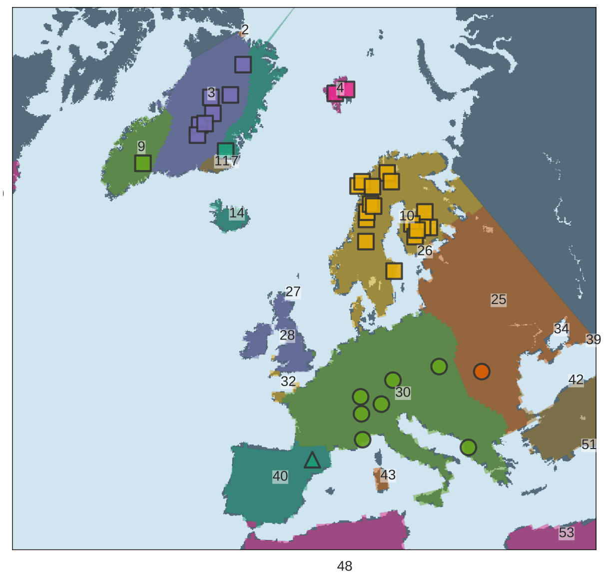
Figure S1. Number of records covering a given year.



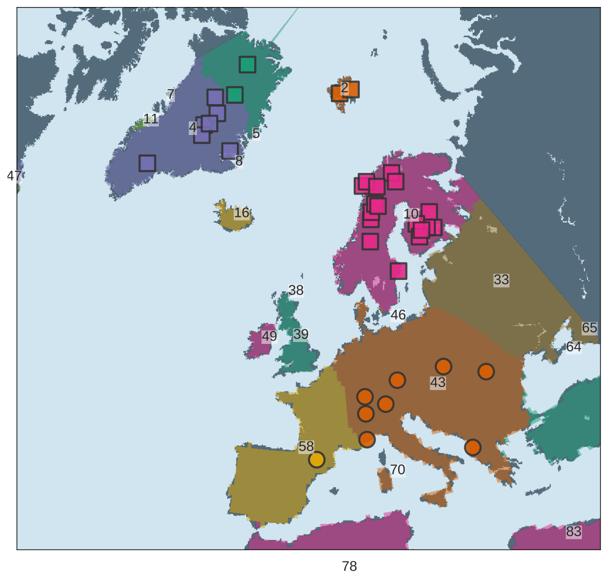
(a) JJA temperature, $\alpha_C = 0.008$



(b) DJF temperature, $\alpha_C = 0.007$



(c) all seasonal temperatures, $\alpha_C = 0.0115$



(d) annual temperature, $\alpha_C = 0.008$

Figure S2. Obtained geographical clusters based on different temperature-related variables obtained from the ERA-20C reanalysis.

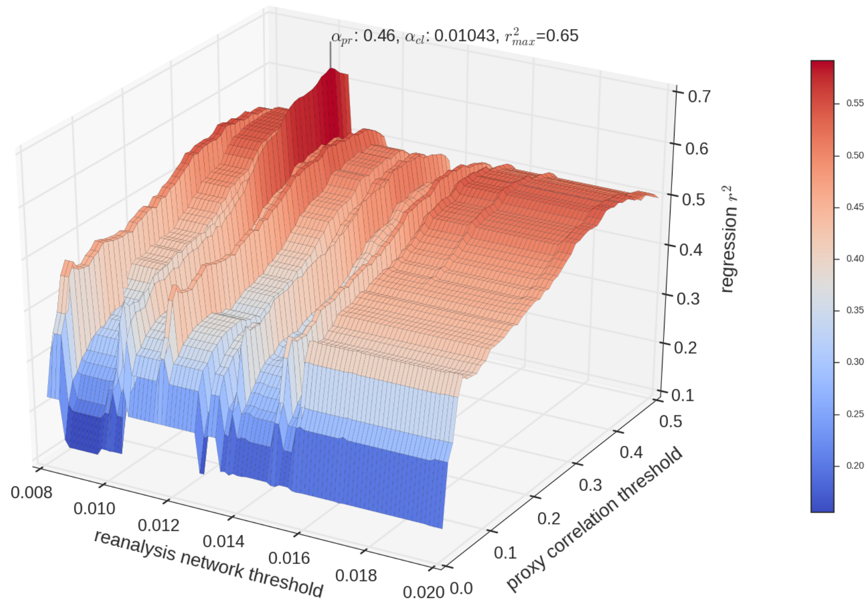


Figure S3. r^2 values of the OLS regression models obtained for different parameter combinations of α_{pr} and α_C. The resulting clusters of each parameter setting (determined by α_C) have been used to fit a linear model (see main text for details) based upon the cross-link densities to the 50 year-averaged NAO reconstruction by Ortega et al. (2015). The parameter values used within the main paper are those that maximize r^2.

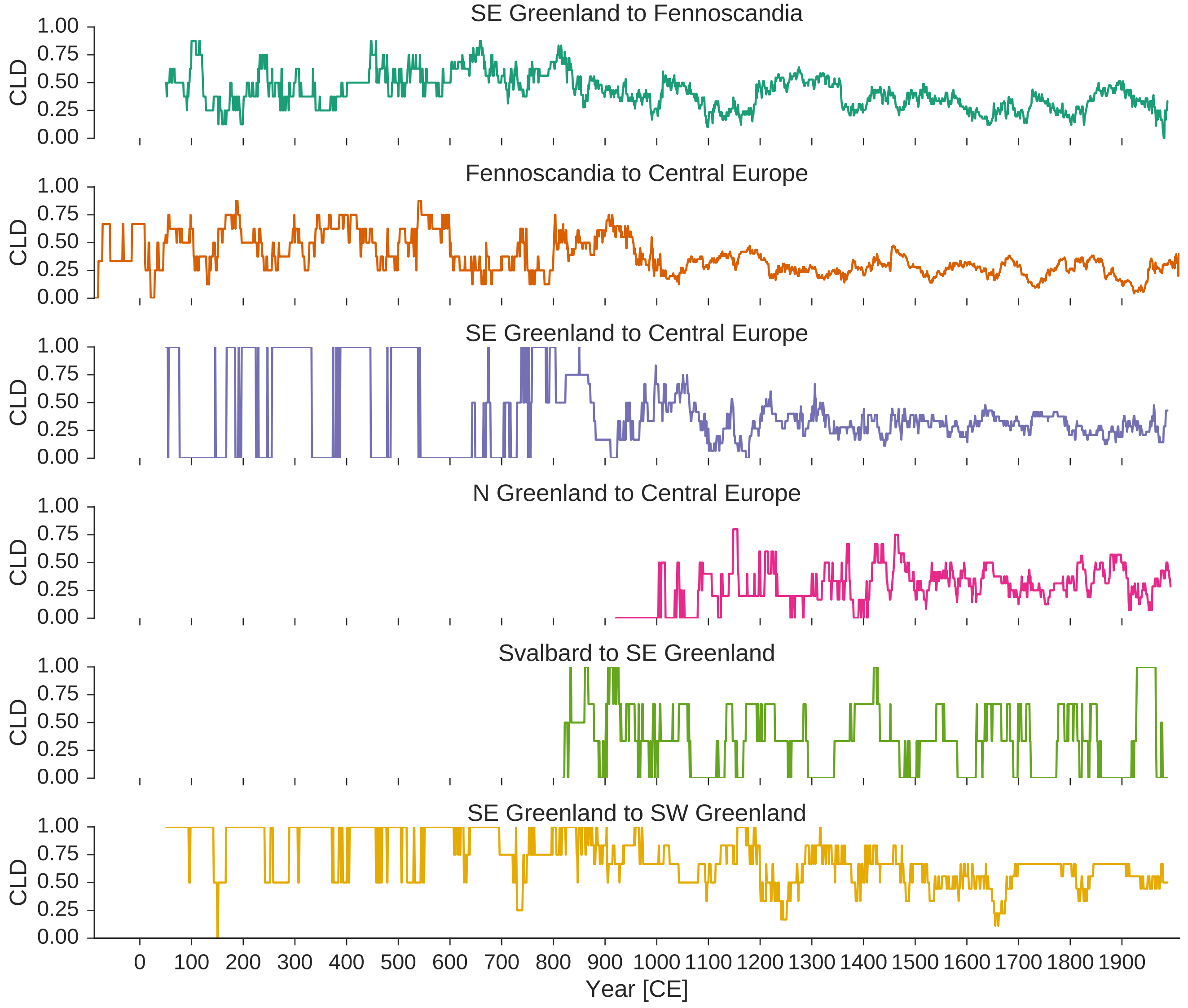


Figure S4. Evolution of the six cross-link densities with the largest regression coefficients of our linear model (see Tab. S3).

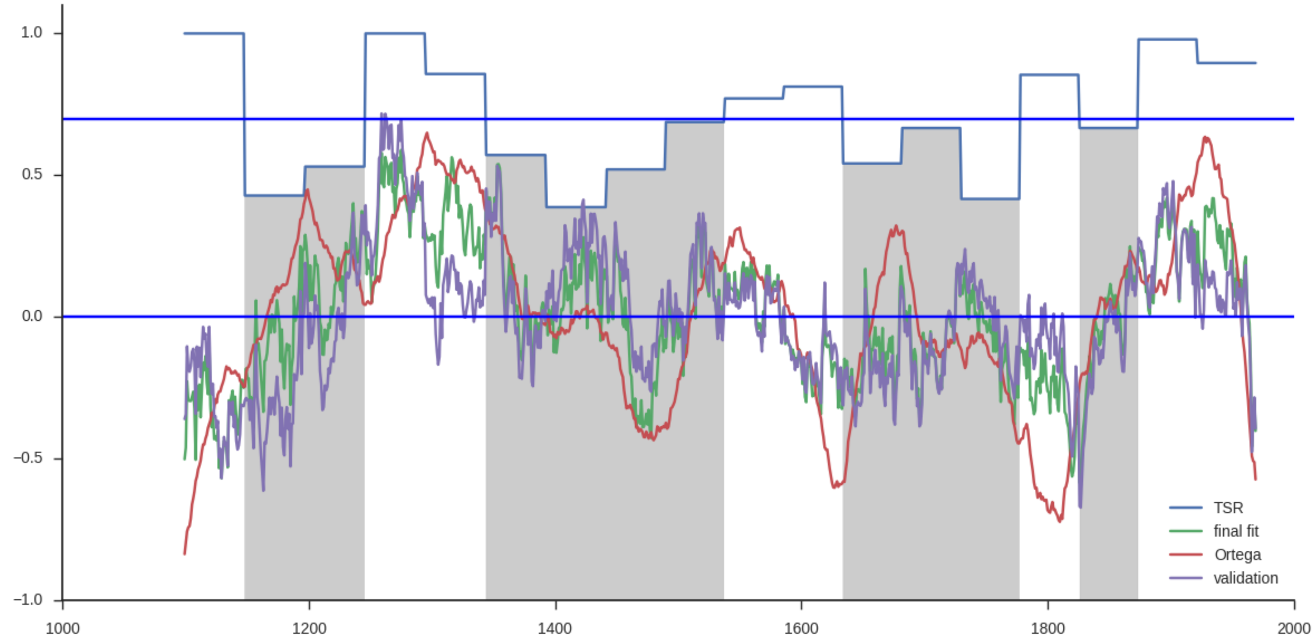


Figure S5. Testing the regression quality by using (mutually exclusive) 50-year time windows as validation data and the rest as training data for our regression model. The red line corresponds to the regression target, the 50-year running average of the NAO reconstruction by Ortega et al. (2015). The purple line indicates the values predicted by our model for each individual time window, the green line denotes the median of the final regression model, and the blue line shows the true sign ratio (TSR) for each window. The horizontal line marks the mean value of TSR (0.69); periods with lower values are shaded in gray.

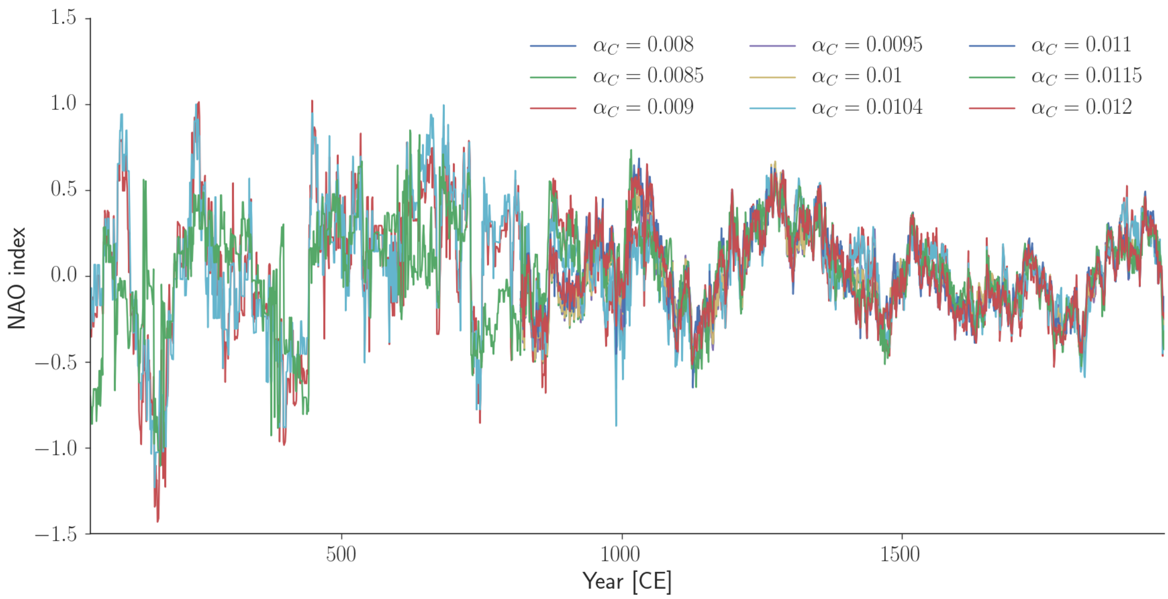


Figure S6. Qualitative NAO reconstructions obtained with different parameters of α_C.

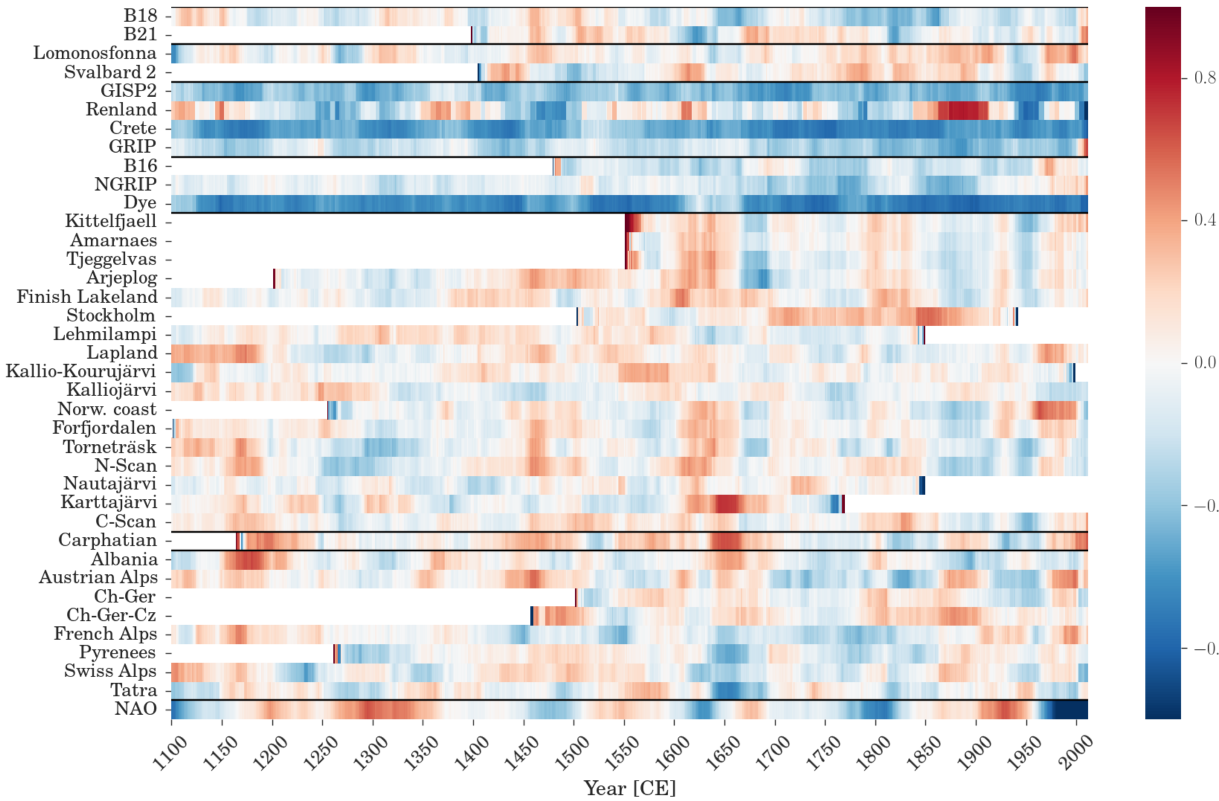


Figure S7. Correlations between the different records used in our study and the NAO reconstruction by Ortega et al. (2015) for 50-year running windows. Spatial clusters as discussed in the main paper are separated by black lines.

Table S1. The data used in this analysis. The corresponding references and data citations can be found in Tab. S2. Those records also used in the reconstruction by Ortega et al. (2015) are printed bold.

name	long. [°W]	lat. [°N]	archive	proxy	variable	first [CE]	last [CE]	res.
Albania	41	20	TR	TRW	TRW index [-]	968	2008	1
Austria	47	10.7	TR	TRW	T [°C]	1	2003	∼1
Ch-Ger-Cz	49	13	hist.		T [°C]	1500	2007	1
Carphatian	47	25.3	TR	TRW	T [°C]	1163	2005	1
French Alps	44	7.5	TR	TRW	TRW index [-]	969	2007	1
Pyrenees	42.5	1	TR	MXD/TRW	T [°C]	1260	2005	1
NScan	68	25 TR	MXD	T [°C]		1	2006	1
Swiss Alps	46.4	7.8	TR	MXD	T [°C]	755	1892	∼1
Stockholm	59.32	18.06	hist.		T [°C]	1502	1892	1
Korttajärvi	62.33	25.68	LS	XRD	XRD	0	1720	1
Kittelfjael	65.2	15.5	TR	MXD	RSF_i	1550	2007	1
Amarnaes	65.9	16.1	TR	MXD	RSF_i	1550	2010	1
Tjeggelvas	66.6	17.6	TR	BI	$BRSF_i$			1
Arjeplog	66.3	18.2	TR	BI	$BRSF_i$	1200	2010	1
Lomonosfonna	78.87	17.425	IC	$\delta^{18}O$	$\delta^{18}O$ [‰]	769	1997	1
Ch-Ger	48	8	hist.		T [°C]	1454	1970	1
GISP2	72.1	-38.8	IC	$\delta^{18}O$	$\delta^{18}O$ [‰]	818	1987	1
Lehmilampi	63.62	29.1	LS	VT	VT [mm]	1	1800	1
Lapland	69	25	TR	TRW	T [°C]	0	2000	1
Svalbard 2	79.83	24.02	IC	$\delta^{18}O$	$\delta^{18}O$ [‰]	1400	1998	∼ 1
Kallio-Kourujärvi	62.33	27.04	LS	VT	VT [mm]	-129	149	1
Kalliojärvi	63.13	25.22	LS	VT	VT [mm]	-137	2000	1
Norw. coast	68.78	15.75	TR	TRW	TRW index	1254	1993	1
Forfjordalen	69.08	17.22	TR	TRW/MXD	trsgi	1100	2007	1
Torneträsk	68.26	19.6	TR	TRW/MXD	T [°C]	-39	2010	1
Nautajärvi	61.81	24.68	LS	OM	OMA	0	1800	1
B16	73.94	-37.63	IC	$\delta^{18}O$	$\delta^{18}O$ [‰]	1478	1992	1
B18	76.62	-36.4	IC	$\delta^{18}O$	$\delta^{18}O$ [‰]	871	1992	1
B21	80	-41.14	IC	$\delta^{18}O$	$\delta^{18}O$ [‰]	1397	1992	1
Tatra	49	20	TR	TRW	T [°C]	1040	2011	1
NGRIP	75.1	-42.32	IC	$\delta^{18}O$	$\delta^{18}O$ [‰]	0	1995	1
Renland	71.27	-26.73	IC	$\delta^{18}O$	$\delta^{18}O$ [‰]	3	1993	5
Crete	71.12	-37.32	IC	$\delta^{18}O$	$\delta^{18}O$ [‰]	553	1973	1
Dye	65.18	-43.83	IC	$\delta^{18}O$	$\delta^{18}O$ [‰]	1	1978	1
GRIP	72.58	-37.64	IC	$\delta^{18}O$	$\delta^{18}O$ [‰]	850	2011	1
CScan	63	14.05	TR	MXD	T [°C]	850	2011	1

Table S2: Further information about the data used in this analysis. The PAGES2k IDs refer to the database published by PAGES2k Consortium (2017). Additional information can be found at the corresponding supplementary material.

name	PAGES2k ID	reference	data citation	URL/DOI
NScan	Eur_003	Esper et al. (2012b)	Esper et al. (2012a)	https://www.ncdc.noaa.gov/paleo/study/1003406
Tatra	Eur_004	Büntgen et al. (2013a)	Büntgen et al. (2013b)	https://www.ncdc.noaa.gov/paleo/study/1003402
Carphatian	Eur_005	Popa and Kern (2009b)	Popa and Kern (2009a)	https://www.ncdc.noaa.gov/paleo/study/1003409
French Alps	Eur_006	Büntgen et al. (2012a)	Büntgen et al. (2012b)	http://www.ncdc.noaa.gov/paleo/study/1003400
Ch-Ger-Cz	Eur_011	Dobrovolný et al. (2010b)	Dobrovolný et al. (2010a)	https://www.ncdc.noaa.gov/paleo/study/1003404
Austria	Eur_006	Büntgen et al. (2011a)	Büntgen et al. (2011b)	https://www.ncdc.noaa.gov/paleo/study/1003403
Swiss Alps	Eur_007	Büntgen et al. (2006a)	Büntgen et al. (2006b)	https://www.ncdc.noaa.gov/paleo/study/1003401
Pyrenees	Eur_009	Dorado Liñán et al. (2012b)	Dorado Liñán et al. (2012a)	https://www.ncdc.noaa.gov/paleo/study/1003405
Lapland	Eur_013	Helama et al. (2009b)	Helama et al. (2009a)	https://www.ncdc.noaa.gov/paleo/study/16790
Stockholm	Eur_019	Leijonhufvud et al. (2010b)	Leijonhufvud et al. (2010a)	https://www.ncdc.noaa.gov/paleo/study/10429
GISP2	Arc_011	Grootes and Stuiver (1997b)	Grootes and Stuiver (1997a)	https://www.ncdc.noaa.gov/paleo/study/17615
Lehmilampi	Arc_014	Haltia-Hovi et al. (2007b)	Haltia-Hovi et al. (2007a)	https://www.ncdc.noaa.gov/paleo/study/8661
Svalbard 2	Arc_018	Isaksson et al. (2005b)	Isaksson et al. (2005a)	https://www.ncdc.noaa.gov/paleo/study/11173
Nautajärvi	Arc_026	Ojala and Alenius (2005b)	Ojala and Alenius (2005a)	https://www.ncdc.noaa.gov/paleo/study/8660
B16	Arc_027	Fischer et al. (1998)	Fischer et al. (2000a)	10.1594/PANGAEA.218274
B18	Arc_028	Fischer et al. (1998)	Fischer et al. (2000b)	10.1594/PANGAEA.57158
B21	Arc_029	Fischer et al. (1998)	Fischer et al. (2000c)	10.1594/PANGAEA.57291
NGRIP	Arc_032	Vinther et al. (2006b)	Vinther et al. (2006a)	https://www.ncdc.noaa.gov/paleo/study/2494
Crete	Arc_034	Vinther et al. (2010d)	Vinther et al. (2010b)	10.1594/PANGAEA.786360
Dye	Arc_035	Vinther et al. (2010d)	Vinther et al. (2010c)	10.1594/PANGAEA.786360
GRIP	Arc_036	Vinther et al. (2010d)	Vinther et al. (2010a)	10.1594/PANGAEA.786360
Renland	Arc_059	Vinther et al. (2008b)	Vinther et al. (2008a)	https://www.ncdc.noaa.gov/paleo/study/11131
Torneträsk	Arc_062	Melvin et al. (2013b)	Melvin et al. (2013a)	https://www.ncdc.noaa.gov/paleo/study/17175

Arjeplog	Arc_065	Björklund et al. (2013a)	Björklund et al. (2013c)	https://www1.ncdc.noaa.gov/pub/data/paleo/PAGES2kID/PAGES2kID-temperature-v2-2017/data-current-version/Arc-Arjeplog.Bjorklund.2014.txt
Amarnaes	Arc_066	Björklund et al. (2013a)	Björklund et al. (2013b)	https://www1.ncdc.noaa.gov/pub/data/paleo/PAGES2kID/PAGES2kID-temperature-v2-2017/data-current-version/Arc-Armarnaes.Bjorklund.2012.txt
Kittelfjael	Arc_068	Björklund et al. (2013a)	Björklund et al. (2013d)	https://www1.ncdc.noaa.gov/pub/data/paleo/PAGES2kID/PAGES2kID-temperature-v2-2017/data-current-version/Arc-Kittelfjall.Bjorklund.2012.txt
Lomonosfonna	Arc_072	Divine et al. (2011b)	Divine et al. (2011a)	https://www1.ncdc.noaa.gov/pub/data/paleo/PAGES2kID/PAGES2kID-temperature-v2-2017/data-current-version/Arc-Lomonosovfonna.Divine.2011.txt
Forfjordalen	Arc_074	McCarroll et al. (2013a)	McCarroll et al. (2013b)	https://www.ncdc.noaa.gov/paleo/study/6346
Tjeggelvas	Arc_077	Björklund et al. (2013a)	Björklund et al. (2013e)	https://www1.ncdc.noaa.gov/pub/data/paleo/PAGES2kID/PAGES2kID-temperature-v2-2017/data-current-version/Arc-Tjeggelvas.Bjorklund.2012.txt
Albania		Seim et al. (2012b)	Seim et al. (2012a)	https://www.ncdc.noaa.gov/paleo/study/1003410
Ch-Ger		Wetter and Pfister (2011b)	Wetter and Pfister (2011a)	https://www.ncdc.noaa.gov/paleo/study/17615
CScan		Zhang et al. (2016b)	Zhang et al. (2016a)	https://www.ncdc.noaa.gov/paleo/study/20429
Kallio-Kourujärvi		Saarni et al. (2015b)	Saarni et al. (2015a)	https://www.ncdc.noaa.gov/paleo/study/22193
Kalliojärvi		Saarni et al. (2016b)	Saarni et al. (2016a)	https://www.ncdc.noaa.gov/paleo/study/22194
Norw. coast		Kirchhefer (2001b)	Kirchhefer (2001a)	https://www.ncdc.noaa.gov/paleo/study/6346
Korttajärvi		Tiljander et al. (2003b)	Tiljander et al. (2003a)	https://www.ncdc.noaa.gov/paleo/study/8659

Table S3. Mean values and standard deviations of the MCMC regression coefficients corresponding to the individual cross-link densities used in this study.

connection	mean value	standard deviation
SE Greenland to Fennoscandia	1.9	0.09
Fennoscandia to Central Europe	- 0.73	0.1
SE Greenland to Central Europe	-0.59	0.09
N Greenland to Central Europe	-0.26	0.05
Svalbard to SE Greenland	0.23	0.05
SE Greenland to SW Greenland	0.21	0.05
Svalbard to Central Europe	0.14	0.04
SE Greenland to Central Europe	-0.13	0.08
N Greenland to SW Greeland	0.11	0.03
N Greenland to SE Greenland	-0.11	0.03
SW Greenland to Fennoscandia	-0.11	0.09
N Greenland to Svalbard	-0.04	0.02
N Greenland to Fennoscandia	0.04	0.08
Svalbard to SW Greenland	-0.03	0.03
Svalbard to Fennoscandia	- 0.003	0.05

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