Clim. Past Discuss., doi:10.5194/cp-2017-33, 2017
Manuscript under review for journal Clim. Past
Discussion started: 31 March 2017

Climate of the Past Discussions

Climate variability in subarctic area for the last two millennia

Marie Nicolle[1], Maxime Debret[1,] Nicolas Massei[1], Christophe Colin[2], Anne deVernal[3], Dmitry Divine[4,5], Johannes P. Werner[6], Anne Hormes[7], Atte Korhola[8] and Hans W. Linderholm[9]

[1] Normandie Univ, UNIROUEN, UNICAEN, CNRS, M2C, 76000 Rouen, France
[2] GEOPS, CNRS, University of Paris-Sud, 91405 Orsay Cedex, France
[3] Centre de recherche en géochimie et géodynamique (Geotop), Université du Québec à Montréal, Montréal, QC, Canada
[4] Norwegian Polar Institute, Tromsø, Norway
[5] Department of Mathematics and Statistics, Arctic University of Norway, Tromsø, Norway
[6] Bjerknes Center for Climate Research and Department of Earth Science, University of Bergen, Bergen, Norway
[7] University of Gothenburg, Department of Earth Sciences, Gothenburg, Sweden
[8] Department of Environmental Sciences, Environmental Change Research Unit (ECRU), University of Helsinki, P.O. Box 65, 00014 Helsinki, Finland
[9] Regional Climate Group, Department of Earth Sciences, University of Gothenburg, 40530 Gothenburg, Sweden

Correspondence to: Marie Nicolle (marie.nicolle2@univ-rouen.fr)

Abstract. To put in perspective the recent climate change, it is necessary to extend the instrumental climate records with proxy data from palaeoclimate archives. Arctic climate variability for the last two millennia has been investigated using statistical and signal analyses from three regionally averaged records from the North Atlantic, Siberia and Alaska based on many sort of proxy data archived in the Arctic 2k database. In the North Atlantic and Alaska areas, the major climatic trend is characterized by long-term cooling interrupted by the recent warming that started at the beginning of the 19th century. This cooling trend is not clearly visible in the Siberian region. The Little Ice Age (LIA) was identified from the individual series and is characterized by an important spatial and temporal expression of climate variability. It started at the earliest by around 1200 AD and ended at the latest in the middle of the 20th century. The large spread temporal coverage of LIA did not show regional consistency or particular spatial distribution and did not show relationship with archive/proxy type either. A focus on the last two centuries shows a recent warming characterized by a well-marked warming trend paralleling with increasing greenhouse gas emissions. It also shows a multi-decadal variability likely due to natural processes acting on the internal climate system variability at regional scale. A 16-30 years cycle is found in Alaska and seems to be linked to the Pacific Decadal Oscillation (PDO) whereas ~20-30 and ~50-90 years periodicities characterize the North Atlantic climate regime, likely in relation with the Atlantic Multidecadal Oscillation (AMO). These regional features are apparently linked to the sea-ice cover fluctuations through ice-temperature positive feedback.

1. Introduction

Since the beginning of the industrial era, the global average temperature have increased by about 1°C and the recent decades have been the warmest in the last 1400 years (PAGES 2k Consortium, 2013; IPCC, 2013). The warming is more pronounced

Clim. Past Discuss., doi:10.5194/cp-2017-33, 2017
Manuscript under review for journal Clim. Past
Discussion started: 31 March 2017

at high latitudes of Northern Hemisphere than in other parts of the Earth (Serreze and Barry, 2011; PAGES 2k Consortium, 2013), being more than twice the rate and magnitude in the Arctic than the global average (Cohen et al., 2014).

To put the present Arctic warming in perspective against the natural climate variability, the instrumental time series are not sufficient. It is thus necessary to extend the climate record back in time with proxy data measured in palaeoclimate archives such as tree rings, ice cores, lake sediment etc.… to help distinguishing the anthropogenic influences from natural forcings (e.g. solar activity, volcanism) and the internal response of the ocean/atmosphere coupled system. Continental multi-proxy reconstructions reveal declining temperature over g the past 2000 years in the Arctic until about 1900 AD, when an important warming of more than 1°C reversed this trend (e.g. Kaufman et al., 2009; Pages 2k Consortium, 2013). Global sea-surface temperature reconstructions from marine archives also indicate global ocean cooling until the beginning of the 19th century (McGregor et al., 2015). The long-term trend correlates with the millennial-scale summer insolation reduction at high northern latitudes (Kaufman et al., 2009) and the increased frequency of volcanic events during the last millennium might also explain some of the cooling episodes that occurred after 1000 AD (PAGES 2k Consortium, 2013; Sigl et al., 2015).

Superimposed to the long-term climate fluctuation, continental-scale temperature reconstructions in the scale of the Northern Hemisphere highlight major climatic warming and cooling pulses during the last millennium, with relatively warm conditions during the Medieval Climate Anomaly (MCA, 950-1250 AD, Mann et al., 2009) and a cold Little Ice Age (LIA, 1400-1700 AD, Mann et al., 2009) period. The LIA is however characterized by an important spatial and temporal variability expression, particularly visible at more regional scale (e.g. Pages 2k Consortium, 2013). It has been attributed to a combination of natural external forcings (solar activity and large volcanic eruptions) and internal sea-ice/ocean feedbacks which fostered long-standing effects of short-lived volcanic events (Miller et al., 2012). A smaller amount of greenhouse gases in the atmosphere may also have contributed to the cooling (Feulner, 2011)

A persistent multidecadal variability in arctic sea-ice and oceanic/atmospheric temperatures variability during the last two millennia was also proposed based on a number of proxies (e.g. Chylek et al., 2011; Miles et al., 2014). The reconstruction of multidecadal oscillations in paleoclimate records offers the possibility to explore the linkages between instrumental and palaeoclimate data and to develop long time series allowing the study of multidecadal variability in the with a high confidence level.

Over the last decade, extensive efforts led to collect and centralize palaeoclimate data available in order to reconstruct past climate variability at regional, hemispheric and global-scales. Most temperature reconstructions include different types of archives and proxies (Morberg et al., 2005; Mann et al., 2009; Kaufman et al., 2009; Ljungqvist, 2010; Marcott et al., 2013) and some studies focused on single palaeoclimate archive type and/or area (e.g. McGregor et al., 2015 for oceans; Weissbach et al., 2016 for ice core; Wilson et al., 2016 for tree rings). Recently, the publication of high time resolution reconstructions by the PAGES 2k Consortium (PAGES 2k Consortium, 2013) and particularly for the Arctic area (Hanhijärvi et al., 2013; McKay and Kaufman, 2014), offers the possibility to study the spatial and temporal pattern of climate variability over large spatial scale from low frequencies (i.e. millennial and multi-centennial fluctuations) to high frequencies such as decadal variations.

In this paper, we use statistical and wavelet analysis in order to characterize long-term and secular (Little Ice Age, LIA) climatic fluctuations that occurred in the Arctic during the past 2000 years, based on a regional data sets. A special attention is given to the last two centuries with the aim to document the respective responses of the climate system to anthropogenic forcing and internal climate variability in the Arctic.

2 Material and Methods

2.1. Database

The records used in this study were compiled by the Arctic 2k working group of the Past Global Changes (PAGES) research programme. This working group released a database for the Arctic area comprising 56 proxy climatic records (version 1.1.1, McKay and Kaufman, 2014).

The database contains all available records for this region that meet several data quality criteria concerning location (from north of 60°N), time coverage (extend back to at least 1500 A.D.), mean resolution (less than 50 years), dating control (at least one age control point every 500 years) (Fig. 1a). For more details concerning the database, see McKay and Kaufman (2014).

Proxy records are from different archive types. Most are continental archives with very reliable chronologies (16 ice cores, 13 tree rings, 19 lake sediment cores and 1 speleothem). Six records are from marine archives and one is a historic record (months of ice cover). Altogether 62% (35 records of 56) of the data are with an annual resolution (Fig. 1b). Therefore, the time resolution of the majority of the Arctic 2k database series offers the possibility to study climate variability of the last two millennia besides the long-term trend, on the broad range of time scales from multi-annual to centennial frequencies.

The database has been built from palaeoclimate proxy series with demonstrated relationship to temperature variability. All the proxy data used have been published in a peer-reviewed journal and the sensitivity of each proxy record to temperature was evidenced either statistically (e.g. correlation with instrumental temperature data) or mechanistically with the description of the processes through which the proxy is shown its sensitiveness to temperature change (McKay and Kaufman, 2014).

The review of all publications associated with the Arctic 2k series reveals some concerns and uncertainties about the temperature controls on proxy. In some case, the correlation between proxy measurements and instrumental temperatures is significant but weak, with a correlation coefficient lower than 0.5 (e.g. Bird et al., 2009; D'Arrigo et al., 2005; D'Arrigo et al., 2009, Spielhagen et al., 2011; Wiles et al., 2014). Such weak relationships suggest that the variability recorded by the proxies are not exclusively linked to temperature but probably also relate to other parameters, climatic or not. In some cases, the authors clearly state that the relationship is not strong enough for reconstructing high resolution variations (D'Arrigo et al., 2005). As there are such uncertainties in the assumed temperature control on proxy, whatever the archive type, we choose to work on the original proxy records directly and not on temperature reconstructions derived from them.

2.2. Regional approach

The climate of the Arctic is influenced, among others, by both the Atlantic and the Pacific oceans, which feature internal variability on different time-scales and specific regional climate impacts.

In the North Atlantic sector, instrumental sea surface temperature (SST) variations since 1860 AD highlight low-frequency oscillations known as the Atlantic Multidecadal Oscillation (AMO) (Kerr, 2000). The AMO corresponds to the alternation of warm and cool phases and has considerable influence on regional climate: the impacts of the AMO were found over the Atlantic, North America and western Europe (e.g. Enfield et al., 2001; Sutton and Hodson, 2005; Knight et al., 2006; Assani et al., 2011).

In the North Pacific, the Pacific Decadal Oscillation (PDO) drives the multidecadal variability (Mantua et al., 1997). It is defined as the leading principal component of monthly SST in the North Pacific Ocean (poleward of 20°N) (Mantua et al., 1997; Mantua and Hare, 2002). Positive phases of PDO are associated with precipitation deficit and positive temperature anomalies in the northwest United States (U.S.), and corresponding precipitation increases in southern Alaska and south western U.S. (Mantua and Hare 2002; Zhang and Delworth, 2015). Conditions are reversed during negative PDO phases.

Based on the recent regional effect of internal atmosphere/ocean oscillations on climate and spatial distribution of the series, we divide the Artic area in three sectors (Fig. 2). The North Atlantic, Alaska and Siberian mean records from these three sectors were obtained from 42, 9 and 5 palaeoclimate series, respectively. The record 9 (see Figs. 1 and 2) located between the North Atlantic and Alaska sectors was finally included to the North Atlantic regional mean record due to the correlation between ring width and Canadian-North American temperatures highlighted by the authors (D'Arrigo et al., 2009). The number of time series used for the Siberian regional averaged record is very low, with only 5 series for a large area (Fig. 2) and the statistical representativeness of the data is thus questionable.

Calculating regional averaged records allows us to investigate the common spatial climate signal of each region and reduce the noise of individual records due to local effect (e.g. Weissbach et al., 2016). Before calculating regional mean records, all records were standardized to report the variations in terms of the standard deviation, which permits to compare the records with each other over the whole record, regardless the parameters and unit values of independent records. The number of data used to calculate each regional mean records increases towards present (Fig. 2e).

2.3. Trends analysis

2.3.1. Mann-Kendall linear trend test

Mann-Kendall test (Mann, 1945 and Kendall, 1975) was used to detect trends in proxy-inferred climate data. It is a non-parametric test commonly employed to detect monotonic trend in climatologic data because it does not require the data to be normally distributed and has low sensitivity to abrupt breaks due to inhomogeneous time series. The null hypothesis H_0 is that the data are independent and randomly ordered. The alternative hypothesis H_1 is that the data follow a monotonic trend over time. The Mann-Kendal test statistic is calculated according to:

Clim. Past Discuss., doi:10.5194/cp-2017-33, 2017
Manuscript under review for journal Clim. Past
Discussion started: 31 March 2017

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{1}$$

with

$$sign(x_j - x_i) = \begin{Bmatrix} +1 & if & (x_j - x_i) > 0 \\ 0 & if & (x_j - x_i) = 0 \\ -1 & if & (x_j - x_i) < 0 \end{Bmatrix} \tag{2}$$

where n is the number of data points, x_i and x_j are the data values in time series i and j ($j > i$), respectively. The variance is defined as follows:

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum\nolimits_{i=1}^{m} t_i\,(t_i-1)(2t_i+5)\right] \tag{3}$$

where p is the number of tied groups in the data set and t_i is the number of data points in the j th tied group. For $n > 10$, the statistic S is approximately normally distributed and computed as:

$$Z_S = \begin{Bmatrix} \dfrac{S-1}{\sqrt{var(S)}} & if & S > 0 \\ 0 & if & S = 0 \\ \dfrac{S+1}{\sqrt{var(S)}} & if & S < 0 \end{Bmatrix} \tag{4}$$

Positive values of Z_S indicate increasing trends while negative Z_S values show decreasing trends. Testing trends is done at the specific α significance level. When $|Z_S| > |Z_{1-\alpha/2}|$, the null hypothesis is rejected and a significant trend exist in the time series. In this study, significance levels α=0.10, α=0.05 and α = 0.01 were used.

A statistic with is closely related to S is Kendall's tau defined by:

$$\tau = \frac{S}{D} \tag{5}$$

where

$$D = \left[\frac{1}{2}n(n-1) - \frac{1}{2}\sum\nolimits_{j=1}^{p} t_j\,(t_j-1)\right]^{1/2}\left[\frac{1}{2}n(n-1)\right]^{1/2} \tag{6}$$

Clim. Past Discuss., doi:10.5194/cp-2017-33, 2017
Manuscript under review for journal Clim. Past
Discussion started: 31 March 2017

The Mann-Kendall's tau statistics will take value between -1 and +1. Positive values indicates that the ranks of both variables increase together, so an increasing trend, while a negative correlation indicates a decreasing trend. The closer to +1 or -1 the value of Kendall's tau, the more significant the trend in the time series.

2.3.1. Locally weighted regression (LOESS)

The locally weighted regression (Cleveland, 1979) was used to investigate systematic features and patterns in the data. It is a method used for smoothing a scatterplot. Contrary to the moving average filtering method, LOESS-filtering allows a well-conservation of the analysed signal variance. The polynomial adjustment is locally performed on the whole series of data: a point *x* is adjusted by the neighbouring points, and weighted by the distance in *x* of these points. The relative weight of each point depends on its distance of *x*: closer the *x*, the more important is its influence on the shape of the regression, and conversely. For this study, we chose a 50 years windows analysis which allows us to investigate long-term fluctuations but also multi-decadal to centennial variability.

2.4. Wavelet Analysis

The Wavelet Transform (WA) is particularly adapted for the study of non-stationary processes, i.e. discontinuities and changes in frequency or magnitude (Torrence and Compo, 1998). Wavelet analysis corresponds to a band-pass filter, which decompose the signal on the base of scaled and translated versions of a reference wave function. Each wavelet has a finite length and is highly localized in time. The reference wavelet ψ comprises two parameters for time-frequency exploration, i.e. scale parameter a and time-localization parameter b so that:

$$\psi_{a,b} = \frac{1}{\sqrt{a}}\,\psi\left(\frac{t-b}{a}\right) \tag{7}$$

The parameter a can be interpreted as a dilation (a>1) or contraction (a<1) factor of the reference wavelet corresponding to the different scales of observation. The parameter b can be interpreted as a temporal translation or phase shift.

The continuous wavelet transforms of a signal $s(t)$ producing the wavelet spectrum is define as:

$$S_{a,b} = \int_{-\infty}^{+\infty} s(t)\,.\,\frac{1}{\sqrt{a}}\,.\,\psi\left(\frac{t-b}{a}\right).\,dt \tag{8}$$

The so-called local wavelet spectrum allows description and visualization of power distribution (z-axis) according to frequency (y-axis) and time (x-axis).

In this study, the Morlet wavelet was chosen as wavelet reference. Several type of wavelets are available but the Morlet wavelet one offers a good frequency resolution and is most of the time used with a wavenumber of 6 for which wavelet scale and Fourier period are approximately equal.

Clim. Past Discuss., doi:10.5194/cp-2017-33, 2017
Manuscript under review for journal Clim. Past
Discussion started: 31 March 2017

All series were zero-padded to twice the data length to prevent spectral leakages produced by the finite length of the time series. Zero-padding produces edge effects and the lowest frequencies and near the edges of the series are underestimated. This are is known as the cone of influence. For this reason, fluctuations that occurs in this area have to be interpreted with caution. Detected fluctuations are statistically tested at α = 0.05 significance level against an appropriate background spectrum, i.e. a red noise (autoregressive process for AR(1)>0) or a white noise (autoregressive process for AR(1)=0) background (Torrence and Compo, 1998). The detected components can be extracted and reconstructed in the time domain by either inverse Fourier or wavelet transform of selected energy bands in the spectrum.

The cross-wavelet spectrum $W_{XY}(a,T)$ between two signals *x(t)* and *y(t)* is calculated according to Eq.(9), where $C_X(a,T)$ and $C^*{}_Y(a,T)$ are the wavelet coefficient of the signal *x(t)* and the conjugate of the coefficient of the wavelet of *y(t)*, respectively:

$$W_{XY}(a,T) = C_X(a,T)C^*{}_Y(a,T) \quad (9)$$

The wavelet coherence is a method that evaluates the correlation between two signals according to the different scales (frequencies) over time. It corresponds to a bivariate extension of wavelet analysis that describes the common variabilities between two series. The wavelet coherence is analogous to the correlation coefficient between two series in the frequency domain. For two signals *x(t)* and *y(t)* se wavelet coherence is calculate as follows:

$$WC(a,T) = \frac{|SW_{XY}(a,T)|}{\sqrt{[|SW_{XX}(a,T).SW_{YY}(a,T)|]}} \quad (10)$$

where S is a smoothing operator.

The wavelet coherence spectrum allows description and visualization of wavelet coherence (z-axis) according to frequency (y-axis) and time (x-axis). Wavelet coherence ranges between 0 and 1, indicating no relationship and a linear relationship between *x(t)* and *y(t)*, respectively.

3 Results and discussion

3.1. Regional records trends

Regional mean records for the three sectors and their corresponding 50-years LOESS filtering are presented in Figures 2 and 3. The North Atlantic and Alaska regional records show well-marked and significant decreasing trends before the beginning of the 19th century: τ=-0.28 (p<0.01; Fig. 3b) and τ=-0.42 (p<0.01; Fig. 3c), respectively. In the Siberian region, no decreasing trend is recorded (τ=-0.02, p=0.22; Fig. 3d). These trends are also found in the analysis of all individual records from that region (Fig. 3a and table S1).

The Subarctic North Atlantic regional record is characterized by two different trends. The first millennium does not show long-term fluctuations, but it is marked by a cold event at ~675 AD, which is consistency with the occurrence of volcanic events (Sigl et al., 2015) and shown by the multi-proxy reconstruction of Hanhijärvi et al (2013) from the Arctic Atlantic region. The second millennium is characterized by a well-marked decreasing trend, particularly clear after ~1250 AD, and ending at ~1810 AD with the commencement of the recent warming phase (Fig. 3b).

The first millennium in the Alaska region is characterized by pronounced decreasing trend of temperatures until ~660 AD followed by an increase until the beginning of the second millennium (Fig. 3c). The cold minimum at ~ 660 AD is recorded only in three time series. During the interval between ~1000 and ~1530 AD, temperatures decreased markedly, followed by a period of slight increase, before the recent warming starting at ~1840 AD in the Alaska area.

In contrary to the subarctic North Atlantic and the Alaska regional mean records, the Siberian regional mean record does not show apparent differences in trend between the first and the second millennium (Fig. 3d). The recent warming is well-marked in the Siberian area and started at ~1820 AD. Notable warm events occurred at ~250 AD, ~990 AD and ~1020 AD.

In the subarctic North Atlantic, the analysis of individual time series reveals inconsistency between the data from marine record 38, which are based on diatoms (Berner et al., 2011) and those of record 39, which are based on Alkenones (Calvo et al., 2002). The two data sets are from the same marine archive (MD 95-2011) but characterized by opposite trends before 1810 AD (Table S1). Data from record 38 shows a significant decreasing trend (τ=-0.18, p<0.01) whereas those from record 39 presents a slightly increasing but non-significant trend (τ=0.14, p=0.14). Different sensitivity to seasonal temperatures possibly explain difference between the two records as previously reported in the Nordic Seas (van Nieuwenhove et al., 2016). In the Arctic-subarctic areas, diatoms often relate to spring bloom whereas Alkenones are produced by coccolithophorids which develop during the warmest part of the summer (e.g. Andruleit, 1997).

Except for some records that characterize warming trends and which can be explained by local particularity or differential seasonal responses, most of the individual series and regional mean records show decreasing trends before the beginning of the 19th century. The millennial-scale cooling trend is consistent with previously published reconstructions from North Atlantic (Hanhijärvi et al., 2013), Arctic (Kaufman et al., 2009; PAGES 2k Consortium, 2013; McKay and Kaufman, 2014) and the Northern Hemisphere (e.g. Morberg et al, 2005; Mann et al., 2008). A robust global cooling trend ending at about 1800 AD was also observed in regional paleoceanographic reconstructions (McGregor et al., 2015). The millennial cooling trend has been attributed to the reduction in summer insolation at high northern latitudes since the beginning of the Holocene (Kaufman et al., 2009), and associated to volcanic and solar forcings, notably during the last millennia (PAGES 2k Consortium, 2013; Stoffel et al., 2015).

At the scale of the Holocene, internal fluctuations occurring at millennial scale have been identified in the subarctic North Atlantic area and were related to the ocean dynamics (Debret et al., 2007, Mjell et al., 2015). Therefore, to better understand the cooling trend of the last two millennia in a larger temporal context taking into account the role of oceanic variability on the long-term temperature variations, longer time series encompassing the entire Holocene would be useful.

Whereas previous studies dates the transition between the long-term cooling and the recent warming at the beginning of the 20th century (e.g. Mann et al., 2008; PAGES 2k Consortium, 2013), we identified here that the cooling trend ended between 1810 and 1840 AD. The evidence of an industrial-era warming starting earlier at the beginning of 19th century was proposed by Abram et al. (2016) for the entire Arctic area. However, the intense volcanic activity of 19th century (1809, 1815, and around

1840, Sigl et al., 2015) may also explain the apparent early warming trend suggesting that it may have been recovery from a exceptionally cool phase.

3.2. Secular variability

Long-term change is not the only variability mode that defines the last two millennial climate, which is also characterized by long standing climatic events such as the Little Ice Age (LIA). Here, we synthetize the expression of the LIA in Arctic-subarctic area based on the Arctic 2k records. The timing of this cold period, which is identified in most series used in this study but not all of them, is taken from the original publications (Fig. 4).

The duration and timing of the LIA in the Arctic-subarctic area are variable from site to site. The earliest starting point is date around 1200 AD (Esper, 2002; Melvin et al., 2013; Larsen et al., 2011) and the youngest ending point is reported to be as late as 1900 AD (e.g. Gunnarson et al., 2011; Isaksson et al., 2005; Linge et al, 2009, Massa et al., 2012) (Figs. 4a and 4b). The time coverage of the LIA ranges between ~100 years (Kirchhefer, 2001) and ~700 years (Melvin et al., 2013). It does not seems to depend upon the location of the data set in space nor to the type of archive or proxy (Fig. 4c). The large range of possible timing for the LIA is consistent with the results of previous study in this area (Wanner et al., 2011). It points to difficulty to distinguishing the LIA cooling in subarctic settings. Actually, individual palaeoclimate series from the northern Greenland area do not clearly record the LIA, but a stack of these series highlighted a cold pulse between the 17th and 18th (Weissbach et al., 2016).

In general, the LIA has been attributed to the combination of external climate forcings including solar activity fluctuations and/or volcanic activity (e.g. Haltia-Jovi et al., 2007; Thomas and Briner, 2009; Helama et al., 2010; Larsen et al., 2011; Berner et al., 2011). In particular, the intensification of volcanic eruption during the last millennium resulted in summer cooling that maintained by sea-ice/ocean feedbacks (Miller et al., 2012).

Although the LIA corresponds to negative temperature anomaly, it is difficult to identify the Arctic area solely based on temperature proxies. The evidence of LIA might also be found in palaeohydrological time series (Nesje & Dahl, 2003). For example, Lamoureux et al. (2001) highlighted the evidence of rainfall increase during the LIA in a varved lake sediment record from the Canadian Arctic. Therefore, it would be relevant to study the LIA from time series which are sensitive to hydrological variability (Linderholm et al., this issue). This would contribute to a better understanding of secular climate variability in the Arctic area and the role of internal climatic system fluctuations on secular variation during the last millennia.

3.3. Recent warming and internal climate oscillation

Studying the climate of the last centuries is an important issue to distinguishing the anthropogenic influences from natural variability and the response of ocean/atmosphere coupled system. The last two centuries are characterized in all region by a well-marked warming trend (North Atlantic sector: τ=0.40, p<0.01; Alaska: τ=0.48, p<0.01; Siberia: τ=0.45, p<0.01) (Fig. 5). The temperature increase of the last two centuries is consistent with the increase of greenhouse gas emissions (Shindell and Faluvegi, 2009). However, the recent warming is not linear as it includes different phases of increase highlighted by the 50-

years LOESS filtering. This is particularly the case in the subarctic North Atlantic sector, where it can be divided in two different periods: 1810 – 1920 AD and 1930 – 2000 AD, with pronounced warming transition phase between 1920 and 1930 AD (Fig. 5a). These results suggest multi-decadal variability, which can be linked with natural internal climate variability mode, superimposed on the increasing anthropogenic trend during the last centuries.

In order to determine the origin of the potential multi-decadal variability in each region, we compared the three regional mean records with two climate indices: the instrumental AMO (Enfield et al., 2001) and PDO (Mantua et al., 1997), using the wavelet coherence (Figs. 6 and 8). The analyses were performed on the time intervals encompassed by the AMO and PDO indices, which are 1856-2000 AD and 1900-2000 AD, respectively. Persistent multi-decadal variability with period of 50-90 years are consistent between the subarctic North Atlantic mean record and the AMO over the last two centuries (1856-2000 AD; Fig. 6c). In the subarctic North Atlantic sector, the 1920-1930 AD transition also coincides with the occurrence of multi-decadal variability with a 20-30 years period similar to the AMO index. The wavelet reconstruction of the 50-90 years oscillation for the subarctic North Atlantic palaeoclimate mean record and the instrumental AMO index reveals that fluctuations are in phase and continuous throughout the last two centuries (Figs. 6a and 6b). Figure 7 presents the addition of the 20-30 years oscillation and the 50-90 years oscillation wavelet reconstructions that corresponds to the part of the AMO that explains the North Atlantic variability during the last centuries.

Comparison with the instrumental PDO index reveals a 16-30 years oscillation common to the Alaska area and the instrumental index during the 1900-2000 AD period (Fig. 8b). The link between the Pacific internal variability and the western Canadian Arctic during the last 700 years was also found by Lapointe et al., 2016 based on comparison between varved record and both instrumental and reconstructed PDO. Wavelet reconstruction of the 16-30 years oscillation for the Alaska palaeoclimate mean record and instrumental PDO index reveals that these scales of fluctuation are in phase, but while they are continuous throughout the last century for the instrumental index (Fig. 8b), this is not the case for the Alaska mean record and. The 16-30 years oscillations only appears after ~1940 AD (Fig. 8a).

Wavelet analysis results show the importance of the role of the internal climate variability on the multidecadal variability in the Arctic Area during the last centuries. The scales of variability found in the Alaska and subarctic North Atlantic sector are linked with PDO and AMO internal climate fluctuations, and these two regional fluctuations are also linked with sea-ice cover fluctuations (Miles et al., 2014; Sha et al., 2015, Lapointe et al., 2016) which may have important feedback impact on climate variability. In fact, the decline in the sea ice cover, with a decrease in the sea ice extend (4% per decade since the end of the 1970's, Cavalieri and Parkinson, 2012), but also ice thickness (50% since 1980 in central Arctic, Kwok and Rothrock, 2009) and the length of the ice season (three-month longer summer ice-free season, Stammerjohn et al., 2012), drive an important heat and moisture transfer to the atmosphere due to the increase of open water surface (Stroeve et al., 2012). This is associated with an increase of surface air temperature, especially in coastal and archipelago areas surrounding the Arctic Ocean (Polyakov et al., 2012). Therefore, while the climate warming in the Arctic accelerates sea ice decline, the sea ice decline simultaneously amplifies and accelerates the recent warming (ice-temperature positive feedback).

4 Conclusion

In this paper, we analysed the paleoclimate record of the last two millennia in the Arctic using a regional approach, based on the specific internal variability. We present three regional mean records for the North Atlantic, Alaska and Siberian area, respectively, based temperature-related proxy records.

The regional approach allowed better understanding of the variability of the Arctic-subarctic area for the last two millennia. In particular, we find a long-term regional variability characterized by long-term cooling, which is reversed by a recent warming that started at the beginning of the 19th century, except in the Siberian sector. However, the low number of time series in that region does not allow us to comment the absence of a trend. Increasing the number of records in this area would be very relevant in order to gain a better understanding of Arctic region climate variability.

A focus on the last two centuries shed light on the climatic change marked by the recent warming linked to global anthropogenic forcing and superimposed by multi-decadal variability related to regional internal climate oscillations (AMO, PDO) and sea-ice cover variability. The identification of these scale of variability is an important issue to better understand multidecadal variabilities occurring in the instrumental data but that cannot be explain because of series not long enough. It allows us to propose linkages between the variations recorded by the palaeoclimate series established from proxy-data on one side and instrumental data on the other side.

Acknowledgments

This is a contribution to the PAGES 2k Network [through the Arctic 2k working group]. Past Global Changes (PAGES) is supported by the US and Swiss National Science Foundations. M.N. was supported by the French Ministry. MD, MN, NM, AD are financed by France Canada research fund and MD, MN and C.C has received funding from the HAMOC project (Grant ANR-13-BS06-0003). We also thanks the FED CNRS 3730: SCALE. We acknowledge all the reviewers for their constructive suggestions and comments.

References

Abram, N. J., McGregor, H. V. , Tierney, J. E., Evans, M. N. McKay, , N. P., Kaufman, D. S. and the PAGES2k Consortium: Early onset of industrial-era warming across the oceans and continents, Nature, 536, 411-418, doi: 10.1038/nature19082, 2016.

Andruleit H.: Coccolithophore fluxes in the Norwegian-Greenland Sea: Seasonality and assemblage alterations, Marine Micropaleontology, 31, 45–64, 1997.

Assani, A.A., Landry, R. and Laurencelle, M.: Comparison of interannual variability modes and trends of seasonal precipitation and streamflow in southern Quebec (Canada). River Res. Appl., 2011.

Berner, K. S., Koç, N., Godtliebsen, F. and Divine, D.: Holocene climate variability of the Norwegian Atlantic Current during high and low solar insolation forcing, Paleoceanography, 26, 245–255, 2011.

Bird, B., Abbott, M., Finney, B. and Kutchko, B.: A 2000 year varve-based climate record from the central Brooks Range, Alaska., J. Paleolim., 41, 25–41, 2009.

Calvo, E., Grimalt, J. and Jansen, E.: High resolution U37K sea surface temperature reconstruction in the Norwegian Sea during the Holocene, Quat. Sci. Rev., 21(12-13), 1385-1394, doi: 10.1016/S0277-3791(01)00096-8, 2002.

Cavalieri, D.J., Parkinson, C.L.: Arctic sea ice variability and trends, 1979-2010. Cryosphere, 6, 881–889, 2012.

Chylek, P., Folland, C.K, Dijsktra, H.A., Lessins, G. and Dubey, M.K.: Ice-core data evidence for a prominent near 20 year time-scale of the Atlantic Multidecadal Oscillation, Geophys. Res. Lett., 38, 13, L13704, 2011.

Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., Francis, J., Dethloff, K., Entekhabi, D., Overland, J. and Jones, J.: Recent Arctic amplification and extreme mid-latitude weather, Nature Geoscience, 7(9), 627-637, 2014.

D'Arrigo, R., Mashig, E., Frank, D., Wilson, R. and Jacoby, G.: Temperature variability over the past millennium inferred from Northwestern Alaska tree rings. Clim. Dyn., 24, 227–236, 2005.

D'Arrigo, A., Jacoby, G., Buckley, B., Sakulich, J., Frank, D., Wilson, R., Curtis, A. and Anchukaitis, K.: Tree growth and inferred temperature variability at the North American Arctic treeline, Global Planet. Change, 65, 71–82, 2009.

Debret, M., Bout-Roumazeilles, V., Grousset, F., Desmet, M., Mcmanus, J. F., Massei, N., Sebag, D., Petit, J.-R., Copard, Y. and Trentesaux, A.: The origin of the 1500-year climate cycles in Holocene North-Atlantic records, Clim. Past, 3, 569-575, 2007.

Enfield, D.B., Mestas-Nunez, A. M. and Trimble P.J: The Atlantic Multidecadal Oscillation and it's relation to rainfall and river flows in the continental U.S., Geophys. Res. Lett., Vol. 28, 2077-2080, doi: 10.1029/2000GL012745, 2001.

Esper, J: Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability, Science, 295, 2250–2253, 2002.

Feulner, G.: Are the most recent estimates for Maunder Minimum solar irradiance in agreement with temperature reconstructions? Geophysical Research Letters, Vol. 38, L16706, doi:10.1029/2011GL048529, 2011.

Gunnarson, B. E., Linderholm, H. W. and Moberg, A.: Improving a tree-ring reconstruction from west-central Scandinavia: 900 years of warm-season temperatures, Clim. Dyn., 36, 97–108, 2011.

Hanhijärvi, S. and Tingley, M.P.: Pairwise comparisons to reconstruct mean temperature in the Arctic Atlantic Region over the last 2,000 years, Clim. Dyn., 41, 2039-2060, doi: 10.1007//s00382-013-1701-4, 2013.

Haltia-Jovi, E., Saarinen, T. and Kukkonen, M.: A 2000-year record of solar forcing on varved lake sediment in eastern Finland, Quat. Sci. Rev., 26, 678–689, 2007.

Helama, S., Fauria, M. M., Mielikainen, K., Timonen, M. and Eronen, M.: Sub-Milankovitch solar forcing of past climates: Mid and late Holocene perspectives, Geol. Soc. Am. Bull, 122, 1981–1988, 2010.

Isaksson, E., Divine D., Kohler, J., Martma, T., Pohjola, V., Motoyama, H. and Watanabe, O.: Climate oscillations as recorded in Svalbard ice core δ18O records between AD 1200 and 1997, Geog. Ann. A, 87, 203–214, 2005.

IPCC Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, USA, 2013.

Kaufman D.S., Schneider, D.P., McKay, .N.P., Ammann, C.M., Bradley, R.S., Briffa, K.R., Miller, G.H., Otto-Bliesner, B.L., Overpeck, J.T., Vinther, B.M. and Arctic Lakes 2k Project Members: recent warming reverses long-term Arctic cooling, Science, 325, issue 5945, 1236-1239, doi: 10.1126/science.1173983, 2009.

Kendall, M.G.: Rank Correlation Methods, Griffin, London, UK, 1975.

Kerr, R.A.: A North Atlantic climate pacemaker for the centuries, Science, 288(5473), 1984-1985, 2000.

Kirchhefer, A.: Reconstruction of summer temperatures from tree-rings of Scots pine (Pinus sylvestris L.) in coastal northern Norway, Holocene, 11, 41–52, 2001.

Knight, J.R., Folland, C.K., Scaife, A.A., 2006. Climate impacts of the Atlantic Multidecadal Oscillation. Geophys. Res. Lett. 33, 1–4, doi: 10.1029/2006GL026242.

Kwok, R. and Rothrock, D.A.: Decline in Arctic sea ice thickness from submarine and ICE Sat records: 1958–2008, Geophys. Res .Lett., 36, L15501, 2009.

Lamoureux, S.F., England, J.H., Sharp, M.J. and Bush, A.B.G.: A varve record of increase "Little ice Age" rainfall associated with volcanic activity, Arctic Archipelago, Canada, The Holocene, 11(2), 243-249, 2001.

Lapointe, F., Francus, P., Lamoureux, S. F., Vuille, M., Jenny, J. P., and Bradley, R. S.: Influence of North Pacific decadal variability on the Western Canadian Arctic over the past 700 years, Climate of the past discussions, 2016.

Larsen, D. J., Miller, G. H., Geirsdóttir, Á. and Thordarson, T.: A 3000–year varved record of glacier activity and climate change from the proglacial lake Hvítárvatn, Iceland. Quat. Sci. Rev., 30, 2715–2731, 2011.

Linderholm, H.W., Nicolle, M., Francus, P., Gajewski, K., Helama, S., Korhola, A., Solomina, O., Yu, Z., Zhang, P., Debret, M., Divine, D., Kauffman, D., Loader, N., Gunnarson, B.E., Routson, C., Seftifgen, K. and Werner, J.: Arctic hydroclimate variability during the last 2000 years – current understanding and research challenges, Clim. Past., Submitted.

Linge H., Lauritzen, S.-E., Andersson, C., Hansen, J.K., Skoglung, R. Ø. And Sundqvist, H.S.: Stable isotope records for the last 10000 years from Okshola cave (Fauske, northern Norway) and regional comparisons, Clim. Past, 5, 667–682, 2009.

Ljungqvist, F. C.: A new reconstruction of temperature variability in the extra-tropical Northern Hemisphere during the last two millennia. Geografiska Annaler: Series A, Physical Geography, 92(3), 339-351, 2010.

Mann, H.B.: Nonparametric test against trend, Econometrica, 13, 245-259, 1945.

Mann, M. E., Zhang, Z., Hughes, M., Bradley, R.S., Miller, S.K., Rutherford, S. and Ni, F.: Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. Proc. Natl Acad. Sci., 105, 13252–13257, 2008.

Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F.: Global Signatures and Dynamical Origins of the Little Ice Age and Medieval Climate Anomaly, Science, 326, 1256–1260, 2009.

Mantua, N.J and Hare S.R.: The Pacific decadal oscillation, J. Oceanogr., 58, 35-44 2002.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M. and Francis, R.C.: A Pacific interdecadal climate oscillation with impacts on salmon production, B. Am. Meteorol. Soc., 78, 1069-1079, 1997.

Marcott S.A., Shakun, J.D., Clark, P.U. and Mix, A.C.: A reconstruction of regional and global temperature for the past 11,300 years, Science, 339, 1198-1201, doi: 10.1126/sciences.1228026, 2013.

Massa, C., Perren, B.B., Gauthier, E., Bichet, V., Petit, C. and Richard, H.: A multiproxy evaluation of Holocene environmental change from Lake Igaliku, South Greenland. J. Paleolim. 48, 241–258, 2012.

McGregor H.V., Evans, M.N., Gosse, H., Leduc, G., Martrat, B., Addison, J.A., Mortyn, P.G., Oppo, D.W., Seidenkrantz, M.-S., Sicre, M.-A., Phipps, S.J., Selvaraj, K., Thirumalai, K., Filipsson, H.L. and Ersek, V.: Robust global ocean cooling trend for the pre-industrial Common Era, Nature Geosci., 8, 671-677, doi:10.1038/NGEO2510, 2015.

McKay, N.P. and Kaufman, D.S.: An extended Arctic proxy temperature database for the past 2,000 years, Sci. Data 1:140026, doi: 10.1038/sdata.2014.26, 2014.

Melvin, T. M., Grudd, H. and Briffa, K. R.: Potential bias in updating tree-ring chronologies using regional curve standardization: Re-processing 1500 years of Torneträsk density and ring-width data, Holocene, 23, 364–373, 2013.

Miles, M.W., Divine, D.V., Furevik, T., Jansen, E., Moros, M. and Ogilvie, A.E.: A signal of persistent Atlantic multidecadal variability in Arctic sea ice, Geophys. Res. Lett., 41, 463-469, doi: 10.1002/2013GL058084, 2014.

Miller, G. H., Geirsdottir, A., Zhong, Y., Larsen, D.J., Otto-Bliesner, B.L., Holland, M.M., Bailey, D.A., Refsnider, K.A., Lehman, S.J., Southon, J.R., Anderson, C., Björnsson, H. and Thordarson, T.: Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks, Geophys. Res. Lett. 39, L02708, doi: 10.1029/2011GL050168, 2012.

Mjell, T. L., Ninnemann, U. S., Eldevik, T., & Kleiven, H. K. F.: Holocene multidecadal-to millennial-scale variations in Iceland-Scotland overflow and their relationship to climate, Paleoceanography, 30(5), 558-569, 2015.

Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M. and Karlen, W.: Highly variable northern hemisphere temperatures reconstructed from low- and high-resolution proxy data, Nature, 433, 613–617, doi:10.1038/nature03265, 2005.

Nesje, A. and Dahl, S.O.: The 'Little Ice Age' – Only temperature? The Holocene, 13, 139–145, 2003.

PAGES 2k Consortium: Continental-scale temperature variability during the past two millennia, Nature Geosci., 6, 339-346, doi: 10.1038/NGEO1797, 2013.

Polyakov, I.V., Walsh, J.E. and Kwok R.: Recent changes of Arctic multiyear sea ice coverage and the likely causes, Bull. Am. Meteorol. Soc., 93, 145–151, 2012.

Serreze, M. C. and Barry, R. G.: Processes and impacts of Arctic amplification: A research synthesis, Glob. Planet. Change, 77(1), 85-96, doi: 10.1016/j.gloplacha.2011.03.004, 2011.

Sha L., Jiang, H., Seidenkrantz, M.-S., Muscheler, R., Zhang, X., Knudsen, M. F., Olsen, J., Knudsen, K. L. and Zhang, W.: Solar forcing as an important trigger for West Greenland sea-ice variability over the last millennium, Quat. Sci. rev., 13, 148-156, doi: 10.1016/quascirev.2015.11.002, 2015.

Shindell, D. and Faluvegi, G.: Climate response to regional radiative forcing during the twentieth century. Nat. Geosci. 2, 294–300, doi: 10.1038/NGEO473, 2009.

Sigl, M., Winstrup, M., McConnell, J. R., Welten, K. C., Plunkett, G., Ludlow, F., Buentgen, 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., Schuepbach, S., Steffensen, J. P., Vinther, B. M., Woodruff, T. E. : Timing and climate forcing of volcanic eruptions for the past 2,500 years, Nature, 523, 7562, 543-549, doi:10.1038/nature14565, 2015.

In: Nature, Vol. 523, No. 7562, 30.07.2015, p. 543-549. Spielhagen, R.F, Werner, K., Sørensen, S.A., Zamelczyk, K., Kandiano, E., Budeus, G., Husum, K., Marchitto, T.M. and Hald, M.: Enhanced modern heat transfer to the Arctic by warm Atlantic water, Science, 331, 450-453, doi: 10.1126/science.1197397, 2011.

Stammerjohn, S., Massom, R., Rind, D. and Martinson, D.: Regions of rapid sea ice change: an interhemispheric seasonal comparison, Geophys. Res. Lett., 39, L06501, 2012.

Stoffel, M., Khodri, M., Corona, C., Guillet, S., Poulain, V., Bekki, S., Guiot, J., Luckman, B.H., Oppenheimer, C., Lebas, N., Beniston, M. and Masson-Delmotte, V.: Estimates of volcanic-induced cooling in the Northern Hemisphere over the past 1,500 years, Nature Geosci., 8, 784-788, doi: 10.1038/NGEO2526, 2015.

Stroeve, J.C., Serreze, M.C., Holland, M.M., Kay, J.E., Maslanik, J. and Barrett, A.P.: The Arctic's rapidly shrinking sea ice cover: a research synthesis, Clim. Change, 110, 1005–1027, 2012.

Sutton, R.T. and Hodson, D. L. R.: Atlantic Ocean forcing of North American and European summer climate, Science, 309(5731), 115-118, 2005.

Thomas, E.K. and Briner, J.P.: Climate of the past millennium inferred from varved proglacial lake sediments on northeast Baffin Island, Arctic Canada, J. Paleolim., 41, 209–224, 2009.

Torrence, C. and Compo, G.P.: A practical guide to wavelet analysis, Bull. Am. Meteorol., 79, 61-78, 1998.

Van Nieuwenhove, N., Baumann, A., Matthiessen, J., Bonnet, S., de Vernal, A.: Sea surface conditions in the southern Nordic Seas during the Holocene based on dinoflagellate cyst assemblages, The Holocene, DOI: 10.1177/0959683615618258, 2016.

Wanner, H., Solomina, O., Grosjean, M., Ritz, S.P. and Jetel, M.: Structure and origin of Holocene cold events, Quat. Sci. Rev., 30, 3109-3123, 2011.

Weissbach, S., Wegner, A., Opel, T., Oerter, H., Vinther, B.M. and Kipfstuhl, S.: Spatial and temporal oxygen isotope variability in northern Greenland – implications for a new climate record over the past millennium , Climate of the Past, 12 ,171-188, doi: 10.5194/cp-12-171-2016, 2016.

Wiles, G. C., D'Arrigo, R., Barclay, D., Wilson, R.S., Jarvis, S.K., Vargo, L. and Frank, D.: Surface air temperature variability reconstructed with tree rings for the Gulf of Alaska over the past 1200 years, Holocene, 24, 198–208, 2014.

Wilson, R., Anchukaitis, K., Briffa, K.R., Büngten, U., Cook, E., D'Arrigo, R., Davi, N., Esper, J., Frank, D., Gunnarson, B., Hegerl, G., Helama, S., Klesse, S., Krustic, 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, Quat. Sci. Rev., 134, 1-18, 2016.

Clim. Past Discuss., doi:10.5194/cp-2017-33, 2017
Manuscript under review for journal Clim. Past
Discussion started: 31 March 2017

Zhang L. and Delworth, T.L.: Analysis of the characteristics and mechanisms of the Pacific Decadal Oscillation in a suite of coupled models from the Geophysical Fluid Dynamics Laboratory. Journal of Climate, 28(19), 7678-7701, doi: 10.1175/JCLI-D-14-00647.1, 2015.

Clim. Past Discuss., doi:10.5194/cp-2017-33, 2017
Manuscript under review for journal Clim. Past
Discussion started: 31 March 2017

Climate of the Past Discussions

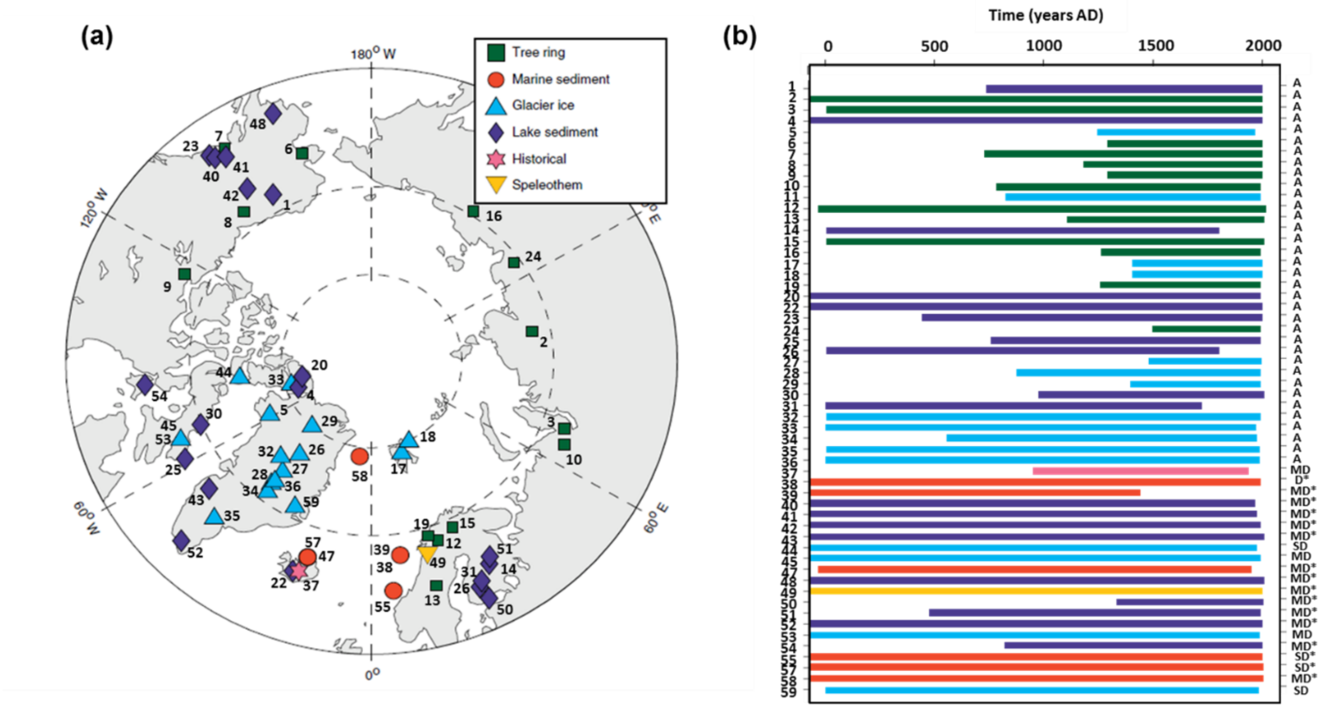

Figure 1. Palaeoclimate series used for this study. (a) Polar projection of the proxy records location contained in the PAGES Arctic 2k database (from McKay and Kaufman, 2014). (b) Temporal coverage and resolution (A: annual, SD: Subdecadal, D: Decadal, MD: Multidecadal) of the records from 0 to 2000 AD. Letters with an asterisk indicate a mean temporal resolution. Colours corresponds to archive type and refers to the map legend and numbers to Arctic 2k database index.

Clim. Past Discuss., doi:10.5194/cp-2017-33, 2017
Manuscript under review for journal Clim. Past
Discussion started: 31 March 2017

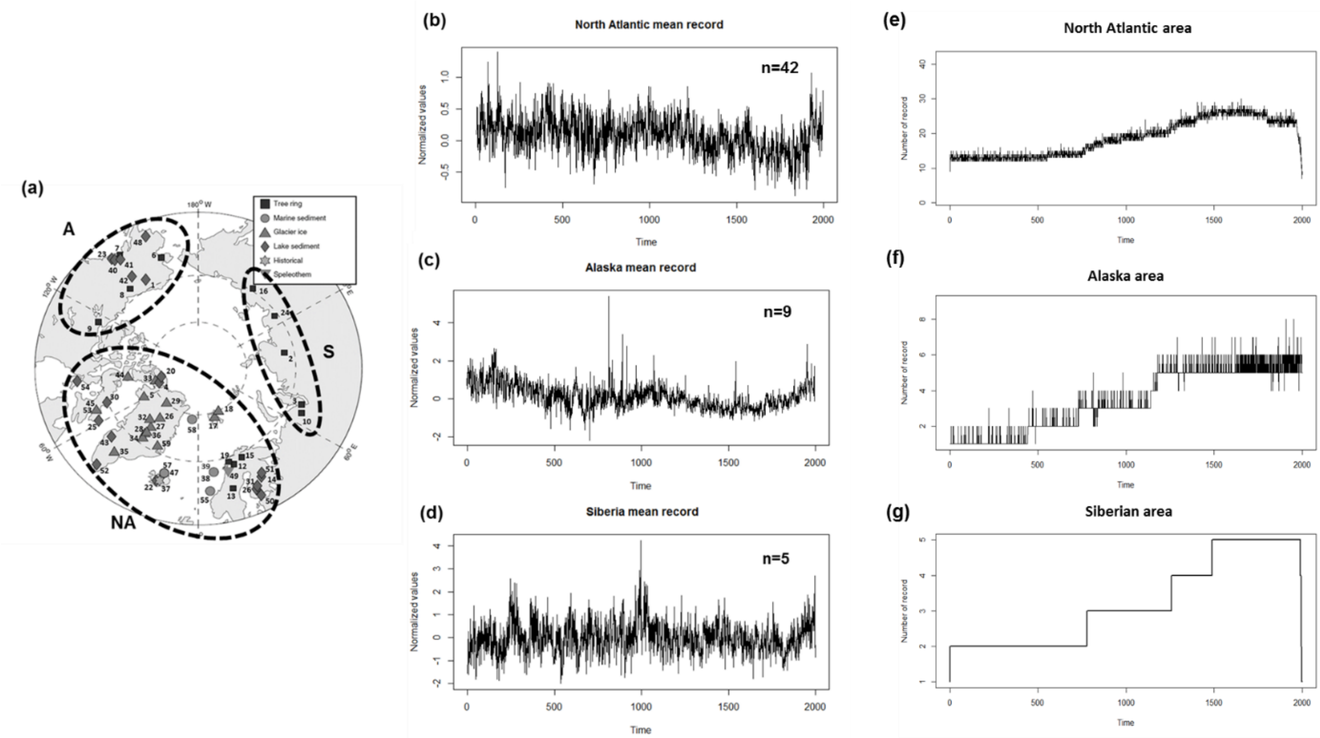

Figure 2. (a) Map of record location (modified from McKay and Kaufman, 2014). Dashed lines show selected area used for calculated North Atlantic (b), Alaska (c) and Siberia (d) regional mean records (NA: North Atlantic, A: Alaska and S: Siberia) and their corresponding number of records available for each year. N corresponds to the number of records available in each area.

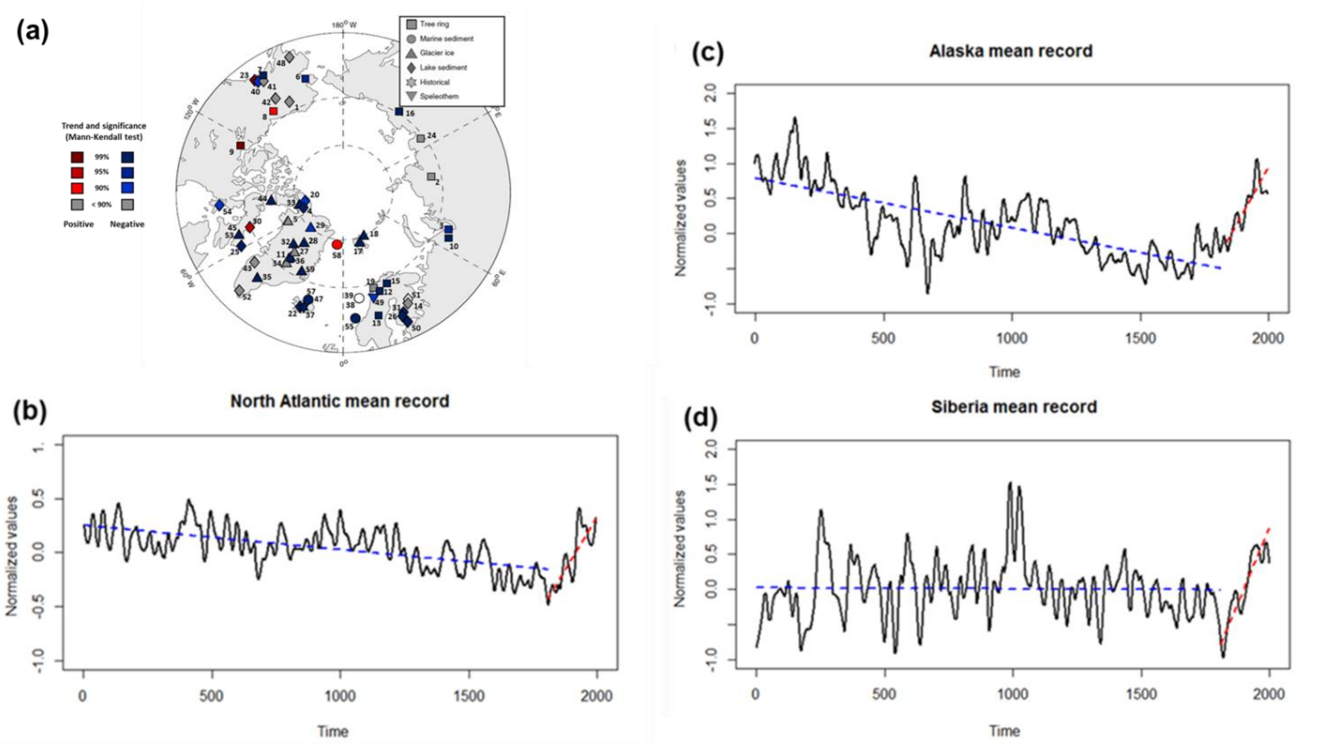

Figure 3. (a) Individual trends for each records before recent warming. North Atlantic (b), Alaska (c) and Siberia (d) regional 50-years LOESS. Blue colours indicate decreasing tendency whereas red colours indicate increasing trends. White dot highlighted inconsistency between two tendencies for the same archive.

Clim. Past Discuss., doi:10.5194/cp-2017-33, 2017
Manuscript under review for journal Clim. Past
Discussion started: 31 March 2017

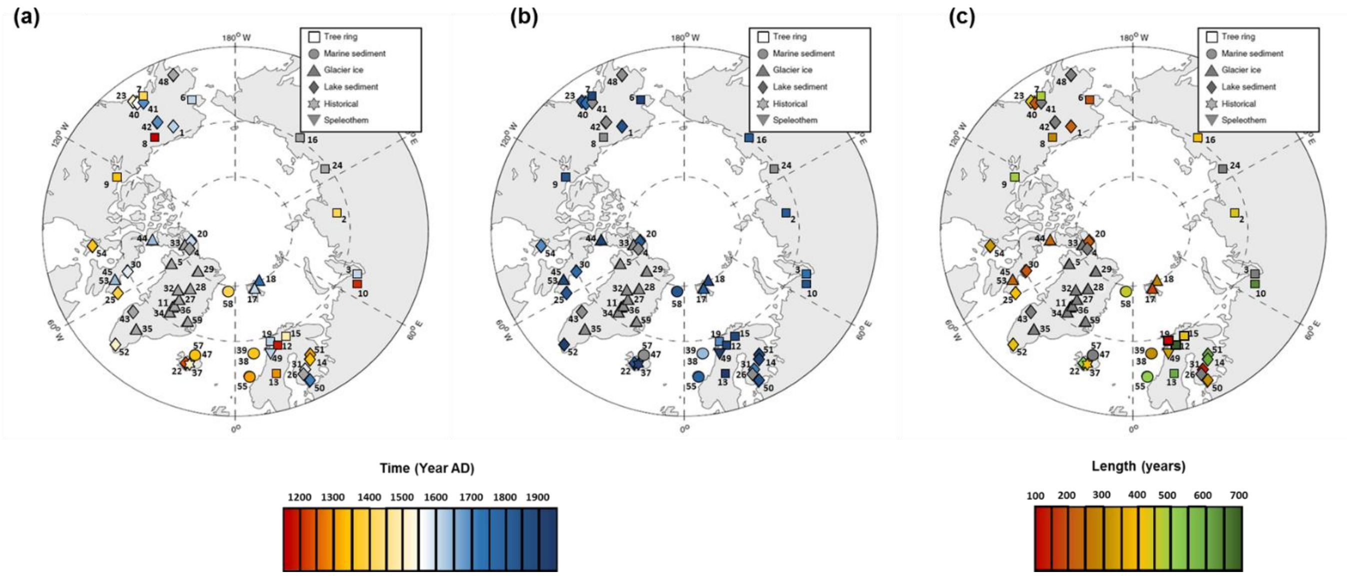

Figure 4. Expression of the Little Ice Age (LIA) of the Arctic 2k series based on references paper (see McKay and Kaufman, 2014): starting (a), ending (b) and length (c). Symbols in grey correspond to series where LIA is not mentioned by the authors.

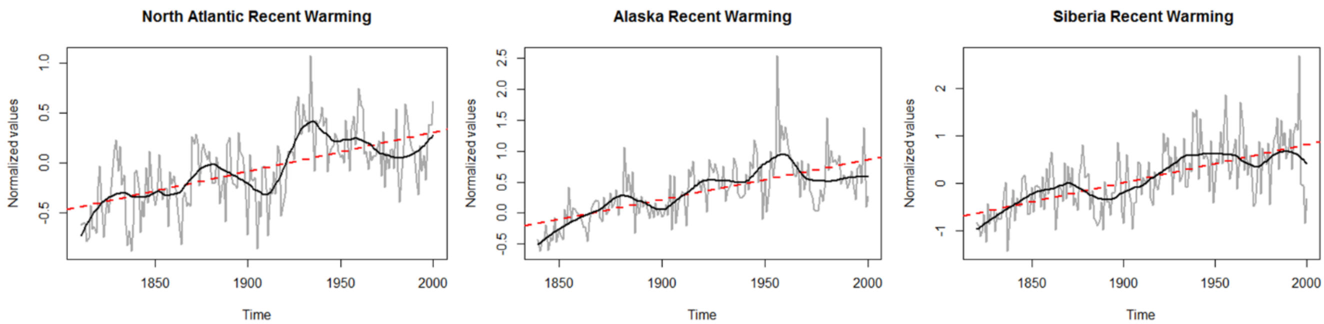

Figure 5. Last centuries regional mean records for the recent warming period. Red dashed lines correspond to linear trend obtained from Mann-Kendall test and black curve to ~50-years loess filtering.

Clim. Past Discuss., doi:10.5194/cp-2017-33, 2017
Manuscript under review for journal Clim. Past
Discussion started: 31 March 2017

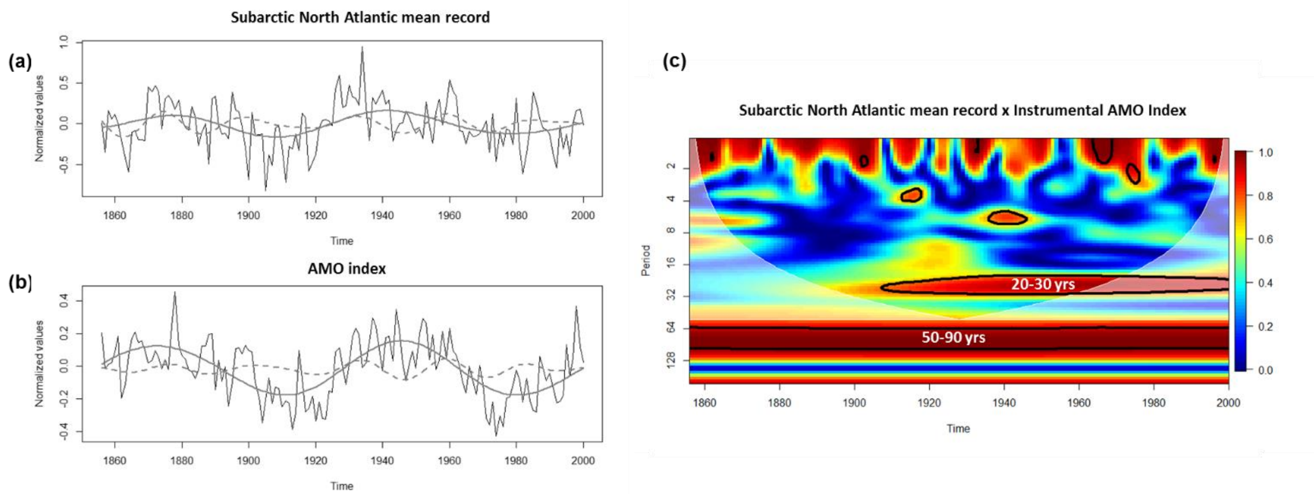

Figure 6. Wavelet coherence analysis between subarctic North Atlantic mean record and instrumental AMO index during the 1856-2000 AD period. (a) Subarctic North Atlantic mean record (this study) and (b) instrumental AMO index (Enfield et al., 2001). Grey lines and dashed lines corresponds to filtered and wavelet reconstructed of the ~50-90 years and ~20-30 years periodicities highlighted on wavelet coherence spectrum (c). Colours on coherence wavelet spectrum represent correlation in both time and frequency domain. (Red equals highest correlation and blue lowest). White line corresponds to the cone of influence. Confidence level of 95% (α=0.05) is indicated with the black line.

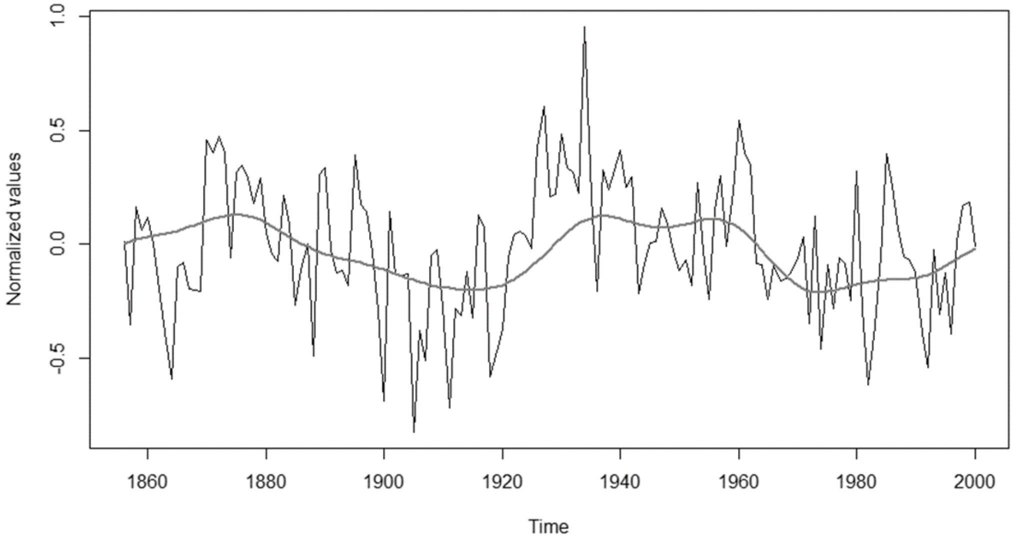

Figure 7. Correspondence between the AMO index reconstructed multidecadal variability (grey line, Enfield et al., 2001) and the subarctic North Atlantic mean record (black line, this study)

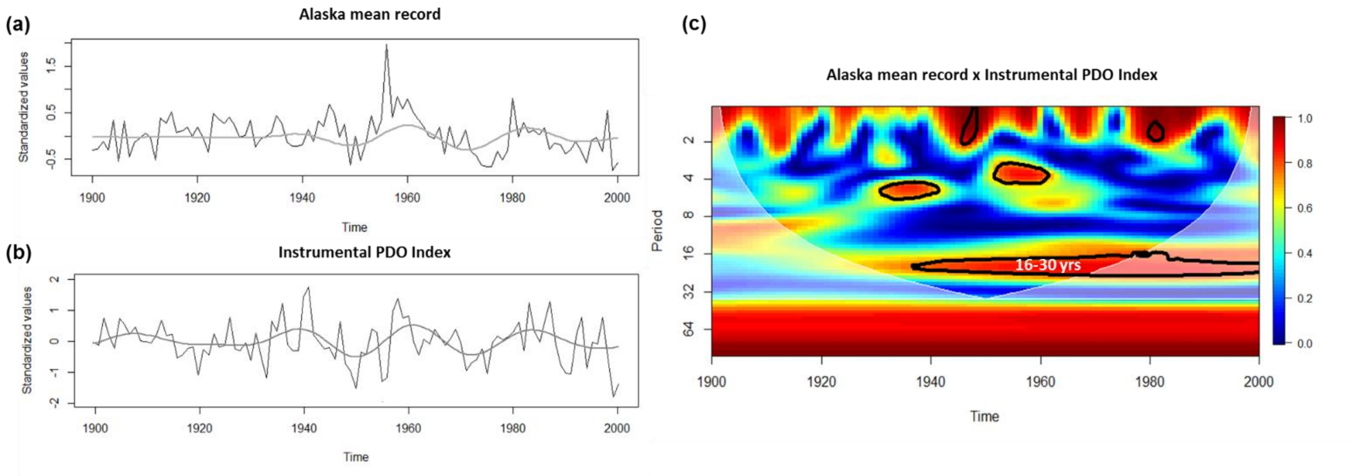

Figure 8. Wavelet coherence analysis between Alaska mean record and instrumental PDO index during the 1900-2000 AD period. (a) Alaska mean record (this study) and (b) instrumental PDO index (Mantua et al., 1997). Grey lines corresponds to filtered and wavelet reconstructed of the ~16-30 years periodicity highlighted on wavelet coherence spectrum (c). Colours on coherence wavelet spectrum represent correlation in both time and frequency domain. (Red equals highest correlation and blue lowest). White line corresponds to the cone of influence. Confidence level of 95% (α=0.05) is indicated with the black line.