The authors and I would like to thank Reviewer #1 for their comments on our submitted manuscript.

Here, I would like to respond to and provide additional details on the Reviewer comments concerning the grouping into three regions (**comments #1, #2 and #3**).
Since the publication of the Arctic 2k database (McKay and Kaufman, 2014), reconstructions of climate variability obtained from the database were published either at the global arctic scale either for a specific region (Scandinavia) (Linderholm *et al.*, 2015). This both spatial scale do not allowed to take into account the role of climatic processes on arctic climate that are well known to have regional climatic impacts nowadays (*e.g.* climatic oscillations as AMO or PDO). We choose a regional approach to refine the comprehension of climate variability in the Arctic area and the three group were determined based on the regional impact of climatic oscillation found in the literature.
We agree that using an EOF analysis would be a good way to find the major patterns existing into the database. However, one of the main objectives of the paper is to determine the ability of the Arctic 2k database series to reproduce climate variability recorded in the observations data, especially during their common period. So that's why we choose to determine our regions based on the regional effect of internal atmosphere/ocean oscillations on climate that are currently recorded in instrumental data and not based on variability recorded in the palaeoclimate series. Regional effect of internal atmosphere/ocean oscillations on climate are describe in the manuscript (p4. L2-13).

Reviewer #1 also suggest to develop the part concerning the internal climate variability (**comment #4**). In fact, one of the most important result of our study is to highlight of the variabilities occurring at multidecadal scales record in paleoclimate data and linked to regional internal climate variability observed in instrumental data. We agree that the use of the recent observations allows us to determine the pattern of influence of PDO and AMO on climate in our study area but also including the role of the sea-ice cover variability. Using recent observations also allow us to compare it with our three regional mean records in order to determine the ability of them to reproduce the climate variability observed.

## References

Linderholm H.W., Björklund J., Seftigen K., Gunnarson B.E. and Fuentes M.: Fennoscandia revisited: a spatially improved tree-ring reconstruction of summer temperatures for the last 900 years, Climate Dynamics , 45(3), 933-947, doi:10.1007/s00382-014-2328-9 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.

My co-authors and I would like to thank the anonymous Reviewer #2 for their comments and suggestions on our submitted manuscript. Here, I would like to provide addition details on the Reviewer #2 comments concerning a better rigorous treatment of uncertainty to put the trends and claimed covariabilities between our regional mean records and the instrumental climate index. For a better understanding, language comments are dissociated for the rest of the specific comments.

**Specific comments:**

- One of the comments of the Reviewer #2 is to be clear when **climatic means temperatures**”. In the update version of the manuscript “Climatic” was modified where it’s appropriate.

- The Reviewer #2 reports an arbitrary **regional grouping of the series**. The spatial density of the data set was the first argument to group the series into three regions, but the regional impact of climatic oscillation observed in instrumental data and found the literature allows to justify that this grouping has a currently climatic reality. In fact, one of the main objectives of the paper is to determine the ability of the Arctic 2k database series to reproduce the regional internal variability recorded in the observations data. May be this objective is not clearly notice in the introduction of the paper and we have to insist on that.

- p4L23**: Standardization** does not change the underlying distribution. It only changes the units. It is used here to compare the proxy series with different units. All the series were individually standardized before calculate each regional mean records.

- The **alpha (α) significance level** is the probability of rejecting the null hypothesis - data are independent and randomly ordered – and a significant trend exist. The term ‘specific’ is not really appropriate and it will be removed in the updated version of the manuscript.

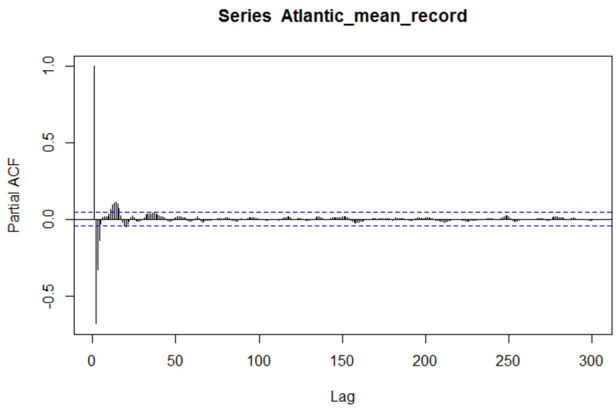
- Concerning the **software packages used**, we propose to add the following sentence into the 2.4 Wavelet analysis section is add in the update version of the manuscript: ‘Wavelet analysis were performed with the software R (Team, 2008) using the packages biwavelet (Gouhier et al., 2012).'

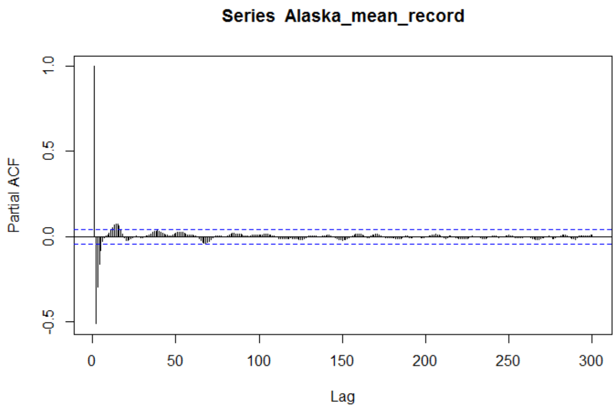
- The size of the **axes labels on Fig. 2** are increase for a better readability.

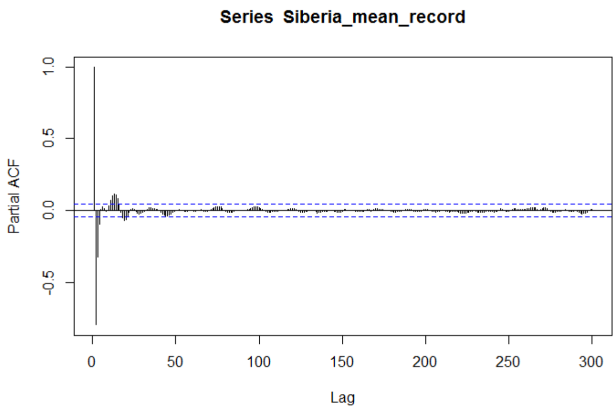
- The Reviewer #2 suggest to **be more specific to explain the difficulty to identify the Little Ice Age** in the Arctic. A paragraph describing the different expressions of the LIA in Arctic will be added to the updated version of the manuscript. A new paragraph will also be added and the same synthesis will be made for the warm period of the MCA, with the update of the Fig. 4.

- It is notice that without uncertainties around regional mean records presented in Fig. 3 and Fig. 5, it is impossible to judge the **significance of the trends**. In the updated version of the manuscript Fig. 3 and Fig. 5, but also Fig. 6, will be modified and the standard deviation curves for the three regional mean records will be added. The addition of the number of records used for each regional mean records and the standard deviation is sufficient to evaluate the uncertainty around regional mean records and so the significance of the trends.

- p9 and 10: Indeed, **p-value** of 0.05 is commonly used for statistical test. If trend detected in the regional mean records are significant at 99% confidence level ($p$-value $< 0.01$), it is also true for a 95% confidence level ($p$-value $< 0.05$). Given that the 95% confidence level is used for the wavelet analysis, we will change this value to homogenize the new version of the manuscript. Autocorrelation and partial autocorrelation was calculated for the three regional mean records (see figures below). Results show that Mann-Kendall trend detected are not linked to autocorrelation in the regional mean records generated.




- Concerning the **uncertainty estimation for the wavelet analysis**, it is includes in the statistical test associated. For all local wavelet spectra, the statistical significance of peaks is assessed using Monte Carlo simulation against an appropriate background noise. Autoregressive modelling is used to determine the AR(1) stochastic process for each time series. AR(1) background noise could be either a red noise (AR(1)>0) or a white noise (AR(1)=0). Each AR(1) is calculated before performed wavelet analysis to determine the background noir used. Concerning the cross-wavelet spectrum, detected fluctuations are statistically tested at $\alpha = 0.05$ significance level against a red noise background. All these precision will be added in the 2.4. Wavelet Analysis part of the manuscript.

- In the update version of the manuscript the part about the link between climatic oscillation (AMO and PDO) and the proxy data will be developed, including the **role of sea-ice cover** on climate. Especially, a new figure will be added and presents the similarity between the trends of the AMO index and the sea-ice cover.

**Language comments:**

All the language mistakes listed by the anonymous Reviewer #2 were taken into account. Specifically:

- p1L18: replaced 'on many sort of proxy data' with 'on multiple proxy type records'
- p1L24: replaced 'show relationship' with 'show a relationship'
- p1L31: replaced 'temperature have' with 'temperature has'
- p2L5: added 's' to 'lake sediments'
- p2L7: added 's' to 'temperatures'
- p2L16: replaced the sentence '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).' with 'The LIA is known to have an important spatial and temporal variability, particularly at regional scale (e.g. Pages 2k Consortium, 2013).'
- p2L26: replaced 'led to' with 'were made to'
- p2L32: added 'a' to 'over a large spatial scale'
- p3L2: replaced 'data sets' with 'data set'
- p3L2: removed 'a' to 'A special attention'
- p4L21: replaced 'regional' with 'regionally'
- p5L5: removed 's' to 'trends'
- p5L8: replaced 'with' with 'which'
- p6L1: removed 's' to 'indicates'
- p6L6: replaced 'well-conservation' with 'conservation'
- p6L14: added 's' to 'decomposes'

- p8L3: replaced ‘pronounced decreasing trend of temperatures’ with ‘decreasing temperatures’
- p9L8: removed ‘date’
- p9L11: replaced ‘seems’ with ‘appear’
- p9L14: ‘removed ‘the’
- p9L28: replaced ‘to’ with ‘for’
- p9L29: added ‘s’ to ‘regions’
- The final paragraph was entirely corrected.

I would like to thank the anonymous Reviewer #3 for their comments and suggestions on the submitted manuscript. Here, I would like to response and provide additional details on the Reviewer #3 comments.

The anonymous Reviewer #3 note that the description of the Mann-Kendall, LOESS filtering and wavelet analysis is not necessary in the manuscript. To reduce the "**Methods" part**, we propose to include it part in several Appendix at the end of the manuscript.

In the new version of the manuscript, the **chapter "Secular variability"** will be modified. The description of the cold period of the LIA will be develop with the addition of a paragraph on the different way of characterizing the LIA in the Arctic area. The same synthesis will be made for the warm period of the MCA, with the update of the Fig. 4. The aims of these part is not the definition of forcings that can cause these two major climatic period and we will focus on the description of the temporal and spatial variability expression of the two periods.

The most important result of our study is the highlighting of variabilities occurring at multidecadal scales record in paleoclimate data and linked to regional internal climate variability observed in instrumental data. So in the update version of the manuscript the part about the link between climatic oscillation (AMO and PDO) and the proxy data will be developed. Especially, a new figure will be added and presents the similarity between the trends of the AMO index and the sea-ice cover to describe the interaction between internal climate variability, sea-ice cover fluctuations and climate variability record in our regional mean records. Because one of the main objectives of the paper is to determine the ability of the Arctic 2k database series to reproduce climate variability recorded in the observations data, we do not used the non-instrumental AMO and PDO records to go father back in time.

My co-authors and I would like to thank Dr. D.S. Kaufman for his comments on our submitted manuscript. Here, I would like to response to the essential additions for this paper highlighted by Dr. D.S. Kaufman:

(1) **Add a "Data Availability" section** :

In the updated version of the manuscript, a "Data availability" section is added with the Data URL for the Arctic 2k database v1.1.1 used in this study.

As suggested also by the Referee #2, the R software (Team, 2008) used to performed the wavelet analysis and the reference associated to the 'biwavelet' package (Gouhier et al., 2012) used for wavelet analysis will also be added in "2.4. Wavelet Analysis section" of the manuscript.

(2) **Add Data Citations and Publication Citations associated to the records** :

In the updated version of Supplementary Material associated to the manuscript, a new Table is added and replace Table S1. It will contains the description of proxy records in the Arctic 2k database arranged by the three regional regions used in the study, but also reference and it DOI for each record.

(3) **Submit the composite temperature time series by region to a public repository** :

We would like to clarify that we do not produce regional composite temperature time series by region but only regional mean records based on proxy data that has previously been standardized. The regional curves obtained will be published online after the publication of this article.

(4) **Why the analyses in this study are based on the old version of the PAGES 2k dataset?**

In the study, we used the Arctic 2k database v1.1.1 (Mc Kay and Kaufman, 2014) because it was the only version publicly available on the date of our manuscript submission (the February 28$^{th}$). As you mentioned, a new Arctic 2k database exists but the reference paper associated is not still publicly available (PAGES 2k Consortium, *in press*; PAGES 2k Consortium, 2017). Without quality criteria of the database it will be difficult to estimate the influence of the use of a new version on the results. Moreover, due to the major difference between the two versions (19 records added and the suppression of 18 records), use the new version does not just correspond to an update of results but means redoing completely the study. This would be very interesting but requires more time and to be the topic of a new paper.

(5) **Archive a table that lists the beginning and ending of the LIA :**

A new Table S3 is added in the Supplementary Material. It will contains the starting and ending dates of the LIA, arranged by the three regional regions used in the study.

**References**

Gouhier, T. and Grinsted, A.: biwavelet: Conduct univariate and bivariate wavelet analyses. R package version 0.20.11, Available at: https://cran.r project.org/web/packages/biwavelet/biwavelet.pdf, 2012.

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.

PAGES 2k Consortium: A global multiproxy database for temperature reconstructions of the Common Era, Scientific Data, in press

PAGES 2k Consortium: A global multiproxy database for temperature reconstructions of the Common Era, version 2.0.0, figshare, https://figshare.com/s/d327a0367bb908a4c4f2, 2017.

Team, R. D. C.: R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available at: URL http://www.r-project.org/, 2008.

List of relevant changes made in the manuscript:

- **The introduction of the manuscript was modified** in order to better explain the objective of the paper: (1) study of the regional climate variability in the Arctic-subarctic area, (2) determine the ability of the proxy records to reproduce instrumental climate variability and (3) role of the internal climate variability during the last two centuries. **The conclusion was also rewrite**.

- To **reduce the** "**Methods" part**, the description of the Mann-Kendall, LOESS filtering and wavelet analysis was include in **several Appendix** at the end of the manuscript.

**- A new part presenting comparison between a global Arctic mean record and the three regional curves was added and developed** to add precision concerning the grouping into three groups. The choice of regional approach is now explain by the spatial distribution of the serie and the groupping is justified by actual regional climatic influence.

- **Confidence interval were add to judge the significance of the LOESS-filtering and the trend in Figures 5 and 8.**

**- The "Secular variability part" was developed** with a synthesis of the expression of the MCA in the Arctic-subarctic region and **a new figure was added** (Fig. 6). **Two supplementary Tables and Figures was also added** (beginning and ending of the LIA and the MCA)

**- A new figure was added and presents the similarity between the trends of the AMO index and the sea-ice cover** to describe the interaction between internal climate variability, sea-ice cover fluctuations and climate variability record in our regional mean records.

- The entire manuscript was corrected by a native English-speaking editor (Edanz, see order in attachment) which help scientists and researchers prepare their work for publication for 20+ years and have built a reputation as the leading author services provider.

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# Climate variability in the subarctic area for the last two millennia

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**Abstract.** To put ~~in perspective the~~ recent climate change in perspective, 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~~ types 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 cooling of the Little Ice Age (LIA) was identified from the individual series, but it ~~and~~ is characterized by ~~an important~~wide range spatial and temporal expression of climate variability, in contrary to the Medieval Climate Anomaly. The LIA~~It~~ started at the earliest by around 1200 AD and ended at the latest in the middle of the 20th century. The ~~large~~ widespread temporal coverage of the LIA did not show regional consistency or particular spatial distribution and did not a 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~~ on a regional scale. A ~16-~~30~~ 30 years cycle is found in Alaska and seems to be linked to the Pacific Decadal Oscillation, ~~(PDO)~~ whereas ~20-~~30~~ 30 and ~50-~~90~~ 90 years periodicities characterize the North Atlantic climate ~~regime~~variability, 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 has increased by about 1°C and recent decades have been the warmest in the last 1400 years (PAGES 2k Consortium, 2013; IPCC, 2013). The warming is more pronounced at high latitudes in the 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 place this warming in the perspective of long-term natural climate variability, the instrumental time series are not sufficient and it is necessary to extend the meteorological measurements back in time with proxy data from in palaeoclimate archives (ice cores, tree-rings, lake sediments, speleothems, marine sediments and historical series).

Over the last decade, extensive efforts have been made to collect and compile palaeoclimate available data to reconstruct past climate variability on 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 a 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). In the Arctic and Subarctic area (90-60°N), several multi-proxy reconstructions of temperatures encompassing the last two millennia were published on a global (PAGES 2k Consortium, 2013; McKay and Kaufman, 2014; Werner et al., 2017) and regional scale (Hanhijärvi et al., 2013).

The annual resolution of these reconstructions allows the study of the climate variability from low frequencies (i.e., millennial and multi-centennial fluctuations) to high frequencies such as decadal variations.

Climatic reconstructions highlighted a millennial cooling trend associated with the monotonic reduction in summer insolation at high northern latitudes, and a reversal marked by an important warming of more than 1°C consistent with the increase of greenhouse gas since the mid-20th century (e.g. Kaufman et al., 2009; Pages 2k Consortium, 2013). The long-term cooling trend correlates with the millennial-scale summer insolation reduction at high northern latitudes (Kaufman et al., 2009) but an increased frequency of volcanic events during the last millennium may also have concurred and contributed to 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 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, particularly visible on a 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 feedback, which fostered long-standing effects of short-lived volcanic events (Miller et al., 2012).

Arctic-subarctic multidecadal climate variability is also influenced by internal climatic system dynamics such as the Atlantic Multidecadal Oscillation (AMO) or the Pacific Decadal Oscillation (PDO), which may impact temperatures and sea-ice cover fluctuations (Chylek et al., 2009). The reconstruction of these oscillations with paleoclimate records offers the possibility to explore the linkages between the internal climate variability and the Arctic-subarctic climate over the last two millennia (e.g. Knudsen et al., 2014; Miles et al., 2014; Wei and Lohmann, 2012).

In this study, we explore the regional expression of the Arctic-subarctic climate variability during the last two millennia using statistical and wavelet analysis. To do so, we define three regions, North Atlantic, Alaska and Siberia, from which we calculated climatic variations. Hence, the regional mean records allowed us to determine if the timing of the long-term and secular (MCA and LIA) climatic fluctuations which occur at the global Arctic-subarctic scale are also characteristic of the regional climate variability. Special attention is given to the last two centuries, with the comparison between the three regional mean records and instrumental climate index, to determine the influence of internal climate variability but also the ability of paleoclimate series to reproduce decadal to multidecadal variability observed in instrumental data.

**Commenté [NA1]:** **Modified in order to better explain the objective of the paper: (1) study of the regional climate variability in the Arctic-subarctic area, (2) determine the ability of the proxy records to reproduce instrumental climate variability and (3) role of the internal climate variability during the last two centuries – Referee #1, Referee #2 and Referee #3**

~~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 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~~2. Paleoclimate data

The records used in this study were compiled by the Arctic 2k working group of the Past Global Changes (PAGES) research program~~me~~. This working group released a database ~~for the Arctic area~~ comprising 56 proxy ~~climatic~~ records for the Arctic area (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 (extending back to at least 1500 A.D.), mean resolution (~~less~~ better than 50 years), and dating control (at least one age control point every 500 years) (Fig. 1a). See Table S1 in supplementary material for more information about each site ~~For more details concerning the database, see~~ (cf. also 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). Among the 56 records, 35 have an annual resolution ~~Altogether 62% (35 records of 56) of the data are with an annual resolution~~ (Fig. 1b). Hence, ~~. Therefore,~~ the high temporal ~~ime~~ resolution of the ~~majority of the~~ Arctic 2k database series offers the possibility to study the high frequency climate variability of the last two ~~millennia~~ millennia~~besides the long-term trend, on the broad range of time scales from multi-annual to centennial frequencies~~, assuming that the proxy record climate variability and the archiving process do not induce a bias in the multi-annual to centennial frequencies analyzed.

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 journals and the sensitivity of each proxy record to temperature was

**Commenté [NA2]:** The analyses are based on the v1.1.1 PAGES 2k dataset because it was the only version publicly available on the date of the manuscript submission. Now, a new version is available but the major difference between the two versions requires a thorough study of the influence of the updating of the database and therefore a new study. – Comment (4) – D.s Kaufman

**Commenté [NA3]:** Table S1 was replace by a new table S1 which contains the description and the URL for each proxy records, arranged by the three regional regions – Comment (2) – D.s Kaufman evidenced either statistically (e.g. correlation with instrumental temperature data) or mechanistically with the description of the processes through which the proxy ~~is shown~~has shown its ~~sensitiveness~~ sensitivity to temperature change (McKay and Kaufman, 2014).

~~The~~ Our review of ~~all~~ the original publications presenting the data used to develop ~~associated with~~ the Arctic 2k ~~series reveals~~database led us to raise some concerns ~~and uncertainties~~ about the actual 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 the mean annueal 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.~~3. Regional approach

The spatial distribution of the series highlights heterogeneity (Fig. 1a). among the 56 series of the Arctic 2k database, 40 (71%) are from the North Atlantic sector, including Scandinavia, Iceland, Greenland and Canadian Arctic, while 11 (20%) represent the Alaska region and 5 (9%) the Siberia. This high spatial discrepancy raises the question of the influence of the over-weighting of the North Atlantic sector on the global Arctic signal. Therefore, to avoid a regional bias, we divide the Artic area into three sectors (Fig. 2a). The record n°9 located in the central part of the Canadian Arctic, between the North Atlantic and Alaska, 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 and the statistical representativeness of the data is thus questionable.

Calculating regionally 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 each regional mean record, all records were standardized over the whole record to report the variations in terms of the standard deviation, which permits comparison of the records with each other, regardless of the parameters and unit values of independent records. The number of data points used to calculate each regional mean record is also indicated (Fig. 2 e-g). The three regional mean records based on the spatial distribution of the series were calculated and then compared with a global Arctic mean record presented in Figure 3.

The correlation between the global Arctic record and the mean North Atlantic record shows a particularly strong relationship (Figure 4b, $r^2 = 0.81$, p-value <<0.05). Correlations are weaker between the Arctic mean and the regional average Alaska record (Figure 4b, $r^2 = 0.23$, p-value <<0.05) or the regional mean Siberian record (Figure 4c, $r^2 = 0.16$, p -value <<0.05). The strong influence of the spatial distribution of data on the global mean Arctic record is also highlighted by the wavelet coherence analysis (see Appendix A for the method description). Wavelet coherence spectra revealed much stronger coherence between the North Atlantic sector and the global Arctic mean than for the two other regions, particularly at low-frequency with common variabilities for periods around 200 (170-220 years) and 500 years (395-540 years), which occur during the last two millennia (Fig. 4d). The coherence spectra between global Arctic mean record and the Alaska regional record shows a significant periodicity around 200 years, for an interval mostly spanning from 1330 to 1900 AD (Fig. 4e). The coherence wavelet spectra between the global Arctic mean and the Siberian mean record does not highlight significant periodicity around the centennial scale except after 1680 AD (Fig. 4f). The comparison between regional mean records and the global Arctic subarctic record highlights climate variability dominated by the North Atlantic signal, which is normal because of the much higher number of time series available in this area. For this reason, we decided to study the Arctic-subarctic climate variability for the last two millennia with a regional approach.

The grouping into the three regions (i.e. North Atlantic, Alaska and Siberia) is justified by present day regional climate. The ~~The~~ climate of the Arctic- subarctic is ~~influenced, among others, by~~influenced by ~~both~~ the Atlantic and the Pacific oceans, which ~~feature~~ experience internal variability on different time-scales ~~and~~ with 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~~ anomalies, which have considerable impact on the ~~and has considerable influence on~~ regional climate~~: the impacts of the AMO were found~~ over the Atlantic, North America and W~~w~~estern 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~~

**Commenté [NA4]:** Developed to precise concerning the way of grouping the data into three groups. The regional approach is now explain by the spatial distribution of the serie and the groupping is confirmed by actual regional climatic influence - Comments (1), (2) and (3) - Referee#1

~~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:~~

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

~~with~~

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

~~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:~~

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

~~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:~~

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

~~Positive values of $Z_S$ indicate increasing trends while negative $Z_S$ values show decreasing trends. Testing trends is done at the specific $\alpha$ 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 $\alpha$=0.10, $\alpha$=0.05 and $\alpha$ = 0.01 were used.~~

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

$$\tau = \frac{S}{D} \quad (5)$$

~~where~~

$$D = \left[\frac{1}{2}n(n-1) - \frac{1}{2}\sum_{j=1}^{p} t_j(t_j - 1)\right]^{1/2} \left[\frac{1}{2}n(n-1)\right]^{1/2} \quad (6)$$

~~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 $\psi$ comprises two parameters for time-frequency exploration, i.e. scale parameter $a$ and time-localization parameter $b$ so that:~~

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

~~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:~~

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

~~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.~~

~~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:~~

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

~~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:~~

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

~~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.~~

## 4~~3~~. ~~Results and discussion~~Regional climate variability during the last two millennia

### 4~~3~~.1. ~~Regional records trends~~Long-term tendencies

Regional mean records for the three sectors and their corresponding 50-year~~s~~ LOESS filtering are presented in Figures 2 and 3. The North Atlantic and Alaska regional records show well-marked and significant decrease~~ing trends~~ before the beginning of the 19th century: τ=-0.28 ($p<<0.01$; Fig. 5~~3~~b) and τ=-0.42 ($p<<0.01$; Fig. 5~~3~~c), respectively. In the Siberian region, no ~~decreasing trend~~decrease is recorded (τ=-0.02, p=0.20; Fig. 5~~3~~d). These trends are also ~~found in~~ shown from the analysis of all individual records from that region (Fig. 5~~3~~a and table ~~S1~~S2). All the regions are characterized by significant warming after the beginning of the 19th century: τ=0.40 ($p<<0.01$) for the North Atlantic, τ=0.48 ($p<<0.01$) for Alaska and τ=0.45 ($p<<0.01$) for Siberia.

The Subarctic North Atlantic regional record is characterized by two different trends. The first millennium does not show long-term fluctuations~~, but~~. However, it is marked by a cold event pulse at ~675 AD, which is depicted in the multi-proxy reconstruction of Hanhijärvi et al. (2013) from the Arctic Atlantic region and coincided with the occurrence of volcanic events (Sigl et al., 2015). ~~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 decreas~~ing trend~~e, particularly clear after ~1250 AD, and ending at ~1810 AD with the ~~commencement~~ onset of the recent warming phase (Fig. 5~~3~~b).

The first millennium in the Alaska region is characterized by a pronounced ~~decreasing trend of~~ decrease in temperatures until ~660 AD followed by an increase until the beginning of the second millennium (Fig. 5~~3~~c). The cold minimum at ~ 660 AD is recorded ~~only~~ in three time series over the five available. 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 c~~Contrary to the subarctic North Atlantic and the Alaska regional mean records, the Siberian regional mean record does not show apparent differences in ~~trend~~ temperature trend between the first and the second millennium (Fig. 5~~3~~d). 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~~ revealed ~~inconsistency~~ inconsistencies between the data from the marine record n°38, which ~~are~~ is based on diatoms (Berner et al., 2011) and ~~those~~ that of record n°39, which ~~are~~ is based on ~~A~~alkenones (Calvo et al., 2002). The two data sets are from the same marine ~~archive~~ core (MD 95-2011) but ~~characterized by~~suggest opposite trends before 1810 AD (Table S2~~1~~). Data from record n°38 shows a significant ~~decreasing~~ decrease ~~trend~~ (τ=-0.18, p<0.01) whereas those from record 39 presents a slight~~ly~~, but non-significant increase ~~increasing but non-significant trend~~ (τ=0.14, p=0.14). Different sensitivity to seasonal temperatures possibly explains the difference between the two records as previously reported ~~in~~ from the Nordic Seas (van Nieuwenhove et al., 2016). In the Arctic-subarctic areas, diatoms often relate to spring bloom, whereas ~~Alkenones~~ alkenones are produced by coccolithophorids, which develop during the warmest part of the summer (e.g. Andruleit, 1997).

Except for some ~~records~~ time series that ~~characterize~~ record warming trends ~~and~~, which can be explained by local ~~particularity~~ effects 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 the 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~~ with volcanic and solar forcings, notably during the last millennia (PAGES 2k Consortium, 2013; Stoffel et al., 2015). Whereas previous studies date~~s~~ 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~~ ~~I~~industrial-era warming starting earlier at the beginning of the 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 an exceptionally cool ~~phase.~~

~~At~~phase. At the scale of the Holocene, internal fluctuations occurring at a millennial scale have been identified in the subarctic North Atlantic area and were tentatively 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, a 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~~4.2. Secular variability

Long-term change is not the only variability mode that defines the last two millennial climate, which ~~is~~ was also characterized by long~~-~~standing climatic events such as the ~~Little Ice Age (LIA)~~LIA and the MCA. Here, we intend to summarize ~~synthetize~~ the expression of the LIA and the MCA in the Arctic-subarctic area based on the Arctic 2k records. The timing of ~~this cold~~these two periods, which ~~is~~ we identified in most but not all of the series used in this study ~~but not all of them~~, is taken from the original publications~~ (Fig. 4)~~. The tables that list the beginning and end of the LIA and the MCA are available in the supplementary material.

**Commenté [NA5]:** A new table S3 was added in the supplementary material and contains the starting and ending dates arranged by three regions. – Comment (5) – D.s Kaufman

**Mis en forme :** Anglais (États-Unis)

The MCA corresponds to a relatively warm period occurring between 950 and 1250 AD (Mann et al., 2009). The starting year of this relatively warm period in the Arctic-subarctic area ranges between 900-950 AD in Siberia and 900-1000 AD in Alaska, which is consistent with the overall records of the Northern Hemisphere (Fig. 6a). In the North Atlantic sector, the MCA began between 800 and 1050 AD, expect in two lake sediments records located in the Canadian Arctic in which the MCA started at the end of the 12th century (Arc_25, Moore et al., 2001; Arc_54, Rolland et al., 2009). The end of the MCA ranges between 1100 and 1550 AD (Fig. 6b). The majority of the records highlight a transition between warmer and colder periods around the 14th century. Two records are characterized by an ending point after the 15th century (Arc_49, Linge et al., 2009; Arc_38, Berner et al., 2011). The time coverage of the MCA is about ~200-250 years in most records (Fig. 6c).

**Commenté [NA6]:** Added to also describe the expression of the warm MCA in the Arctic area – Referee #3

The duration and timing of the LIA in the Arctic-subarctic area are more variable from site to site than the MCA, particularly for the starting year (Fig. 7a). The earliest starting point is dated around 1200 AD (Esper, 2002; Melvin et al., 2013; Larsen et al., 2011) and the~~ youngest~~ earliest 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. 7~~4~~a and 7~~4~~b). The time coverage of the LIA ranges between ~100 years (Kirchhefer, 2001) and ~700 years (Melvin et al., 2013). It does not seem~~s~~ to depend upon the location of the data set in space nor~~ to~~ the type of archive or proxy (Fig. 7~~4~~c). 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~~ did not clearly record the LIA, but a stack of these series highlighted a cold pulse between the 17th and 18th century (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 the negative temperature anomaly, it is difficult to identify the Arctic area solely based on temperature proxies. ~~The evidence~~ Evidence of the LIA might also be found in a palaeohydrological time series (Nesje ~~&~~ and Dahl, 2003). For example, Lamoureux et al. (2001) highlighted the evidence of rainfall increase during the LIA in a varved lake sediment ~~record~~ core from the Canadian Arctic. Therefore, it would be relevant to study the LIA ~~from~~ by using ~~time~~ palaeoclimate 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~~4.3. Recent warming and internal climate oscillation

Studying the climate of the last centuries is a means to examine the ~~an~~ important issue ~~to distinguishing~~of distinguishing ~~the~~ anthropogenic influences from natural variability and the response of an ocean/atmosphere coupled system. The last two centuries ~~are~~ were characterized in all region by a well-marked warming trend (North Atlantic sector: $\tau$=0.40, p<0.01; Alaska: $\tau$=0.48, p<0.01; Siberia: $\tau$=0.45, p<0.01) (Fig. ~~8~~8). The temperature increase ~~of~~ recorded over the last two centuries is consistent with the increase of greenhouse gas emissions (Shindell and Faluvegi, 2009). However, the recent warming ~~is~~ was not linear, as it ~~includes~~ included different phases of increase highlighted by the 50-year~~s~~ LOESS filtering. This is particularly the case in the subarctic North Atlantic sector, where ~~it can be divided in two different periods~~different periods are distinguished with~~: 1810 – 1920 AD and 1930 – 2000 AD, with~~ a pronounced warming transition phase between 1920 and 1930 AD (Fig. ~~8a~~8a). These~~. These~~ results suggest the occurrence of multi-decadal variability superimposed on the increasing anthropogenic trend during the last centuries and ~~,~~ which can be linked with a natural internal climate variability mode~~, superimposed on the increasing anthropogenic trend during the last centuries~~.

~~In order to~~To determine the origin of the ~~potential~~ multi-decadal variability in each region, we compared the three regional mean records with two instrumental climate indices: the ~~instrumental~~ AMO (Enfield et al., 2001) and the PDO (Mantua et al., 1997), using the wavelet coherence (Figs. ~~9~~ 9 and ~~10~~10, Appendix A). Because one of the main objectives of the paper is to determine the ability of the Arctic 2k database series to mimic the climate variability recorded in the observation data, we did not use the non-instrumental AMO and PDO records to go farther back in time. The analyses were thus performed on the time intervals ~~encompassed~~ used to define ~~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. ~~9c~~9c). However, this scale of variability is located in the cone of influence. Comparison of the reconstruction of the 50-90 years oscillation with the original data for each series allowed us to verify if this fluctuation truly characterizes the original signal (Fig. 9a and 9b). It also revealed that fluctuations are in phase and continuous throughout the last two centuries. 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. 9a and 9b).~~ Comparison with the instrumental PDO index ~~reveals~~ revealed a 16-30 years oscillation common to the Alaska area and the instrumental index during the 1900-2000 AD ~~period~~ interval (Fig. ~~10b~~10b). Wavelet reconstruction of the 16-30 years oscillation for the Alaska palaeoclimate mean record and instrumental PDO index reveal~~s~~ed that these scales of fluctuation are in phase. However~~, but~~ while they ~~are~~were continuous throughout the last century for the instrumental index (Fig. 10b), ~~this is not the case for the Alaska mean record and. The~~the 16-30 years oscillations only appear~~s~~ after ~1940 AD in the Alaska record (Fig. 10a).

Internal climate fluctuations are also linked with sea-ice cover fluctuations, which is an important component of the climate system at high latitude (Miles et al., 2014; Sha et al., 2015, Screen et al., 2016). The relationship between the AMO, the sea-ice extent fluctuations and climate variability recorded in the North Atlantic is well-illustrated from 1979 to 2000 (Figure 11).

The decline in the sea ice cover was marked by a decrease in the sea ice extent (4% per decade since the end of the 1970's, Cavalieri and Parkinson, 2012), but also ice thickness (50% since 1980 in the central Arctic, Kwok and Rothrock, 2009) and the length of the ice season (a three-month longer summer ice-free season, Stammerjohn et al., 2012). It was accompanied by heat and moisture transfer to the atmosphere owing 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).

~~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. 10b), this is not the case for the Alaska mean record and. The 16-30 years oscillations only appears after ~1940 AD (Fig. 10a).~~

~~W~~Comparison between our three regional mean records and climate index ~~avelet analysis results~~ shows the ability of regional proxy-based records to reproduce variability that occurrs at multidecadal scales in instrumental data~~-~~, but also the importance of the role of ~~the~~ internal ~~climate~~ variability on the ~~multidecadal variability~~climate 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~~5. Conclusion

With the publication of the PAGES Arctic 2k database, which contains proxy time series that respond to several quality criteria, it was possible to describe the climate in the Arctic-subarctic region over the last 2000 years from low to high frequency variabilities. Long-term tendency, secular variability, and multidecadal fluctuations with a focus on the last 200 years were described using statistical and signal analysis methods.

We presented three new regional mean records for the North Atlantic, Alaska and Siberia regions. Owing to the uncertainties concerning the relationship between several proxy measurements and instrumental temperatures, climate variability has been studied based on proxy time series rather than temperature reconstructions. A large number of proxy time series in the PAGES Arctic 2k database are from the North Atlantic region, but the Siberia region, and to a lesser extent the Alaska region, are underrepresented. Therefore, the global Arctic-subarctic record is probably biased toward the North Atlantic climate variability. Increasing the number of series in the Pacific Arctic, western North America and Siberia would be relevant to gain a better understanding of the global Arctic-subarctic climate variability over the last two millennia.

Despite the spatial heterogeneity of the database, we found regional long-term tendencies similar to the millennial cooling trend recorded at the global Arctic-subarctic spatial scale, except in the Siberia region. Nevertheless, the three regions are characterized by a recent warming starting at the beginning of the 19$^{th}$ century.

Synthesis of the expression of secular fluctuations has shown the spatial and temporal variability of the cold LIA. The definition of the LIA as a major climate event is therefore equivocal, unlike the warm MCA, which seems more evenly represented.

The focus on the last two centuries led to highlight that the recent warming was marked by a global increasing temperature trend linked to the anthropogenic forcing. It was also punctuated by climatic fluctuations related to regional internal climate oscillations that occur at multidecadal scales, especially the AMO in the North Atlantic region and the PDO in the Alaska region. The identification of this variability in the proxy-based records raises the important issue of the need to better understand regional past climate variability in the Arctic-subarctic area. Comparison between regional proxy-based records and instrumental climate index also lead to proposde linkage between paleoclimate series on one side and instrumental data on the other.

**Commenté [NA7]:** Completely rewritten – Referee #2

~~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 19$^{th}$ 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**

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**Data availability**

The PAGES Arctic 2k database used is this study (v1.1.1) is archived at the National Oceanic and Atmospheric Administration's World Data Center for Paleoclimatology (WDC-Paleo) and available at https://www.ncdc.noaa.gov/paleo/study/16973. The database is also archived on Figureshare and available at https://figshare.com/articles/Arctic_2k_v1_1/1054736/5.

**Commenté [NA8]:** Section added - Comment (1) – D.s Kaufman The three regional mean records will be published on Figshare too after acceptance.

**Appendix A. 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 decomposes 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 $\psi$ 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 transform of a signal $s(t)$ producing the wavelet spectrum is defined 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 types of wavelets are available, but the Morlet wavelet offers a good frequency resolution and is most often used with a wavenumber of 6, for which wavelet scale and Fourier period are approximately equal.

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 the area near the edges of the series is underestimated. This area is known as the cone of influence. For this reason, fluctuations that occur 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). Autoregressive modelling is used to determine the AR(1) stochastic process for each time series. 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)* the 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.

Wavelet analysis were performed with the software R (Team, 2008) using the packages biwavelet (Gouhier et al., 2012).

**Commenté [NA9]:** Referee #2

## Appendix B.

The locally weighted regression (Cleveland and Delvin, 1988; Cleveland and Loader, 1996) 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 analyzed signal variance. The polynomial adjustment is locally performed on the whole series of data: a point *x* is adjusted by the neighboring points, and weighted by the distance in *x* of these points. The relative weight of each point depends on its distance from *x*: the closer the *x*, the more important its influence on the shape of the regression, and vice versa. For this study, we chose a 50 years window analysis, which allows us to investigate long-term fluctuations and multi-decadal to centennial variability.

For each individual record, a 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 trends 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. For $n > 10$, the statistic $S$ is approximately normally distributed and positive values of $Z_S$ indicate increasing trends while negative $Z_S$ values show decreasing trends. Testing trend~~s~~ is done at the ~~specific~~ α significance level. When $|Z_S| \geq |Z_{1-\alpha/2}|$, the null hypothesis is rejected and a significant trend exists in the time series. In this study, significance levels α=0.10, α=0.05 and α = 0.01 were tested. A statistic ~~that~~ is closely related to $S$ is Kendall's tau. It will take a value between -1 and +1. Positive values indicate that the ranks of both variables increase together, meaning 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.

**Commenté [NA10]:** To reduce the "Methods part", Appendix were added. – Referee #3

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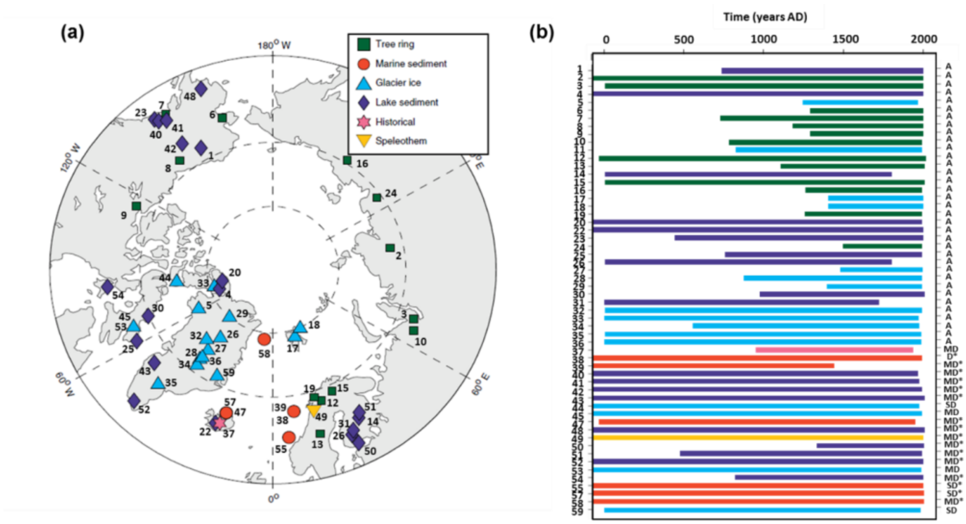



**Figure 1.** Palaeoclimate series used for this study. (a) Polar projection of the proxy records location contained in the PAGES Arctic 2k database (from McKay and Kaufman, 2014). (b) Temporal coverage and resolution (A: annual, SD: Subdecadal, D: Decadal, MD: Multidecadal) of the records from 0 to 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~~ in the Arctic 2k database index.

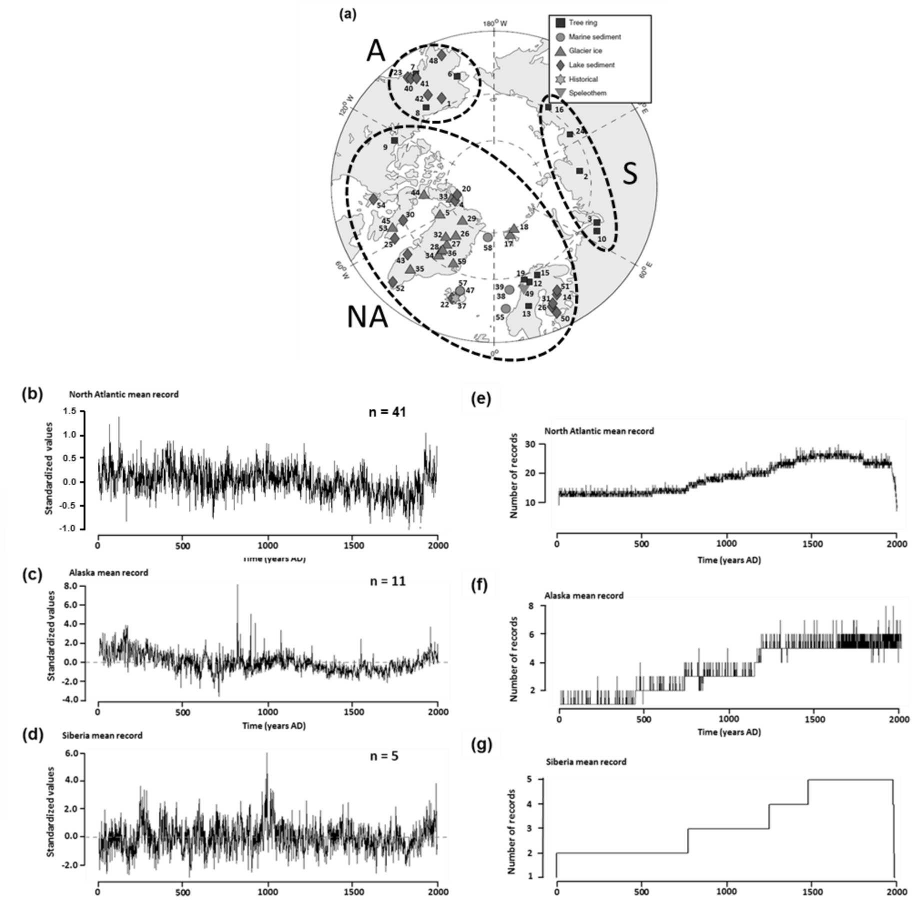



**Figure 2.** (a) Map of record location (modified from McKay and Kaufman, 2014). Dashed lines show selected area used for calculated the three regional mean records (NA: North Atlantic, A: Alaska and S: Siberia) presented at the (b), (c) and (c) curves respectively. n corresponds to the number of records available in each area. Each regional mean record is associated to it corresponding number of records available for each year.

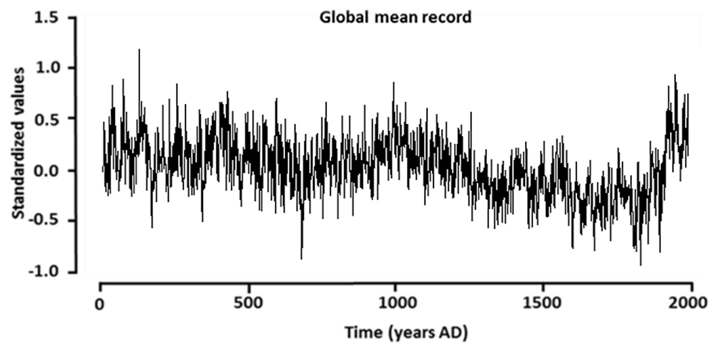
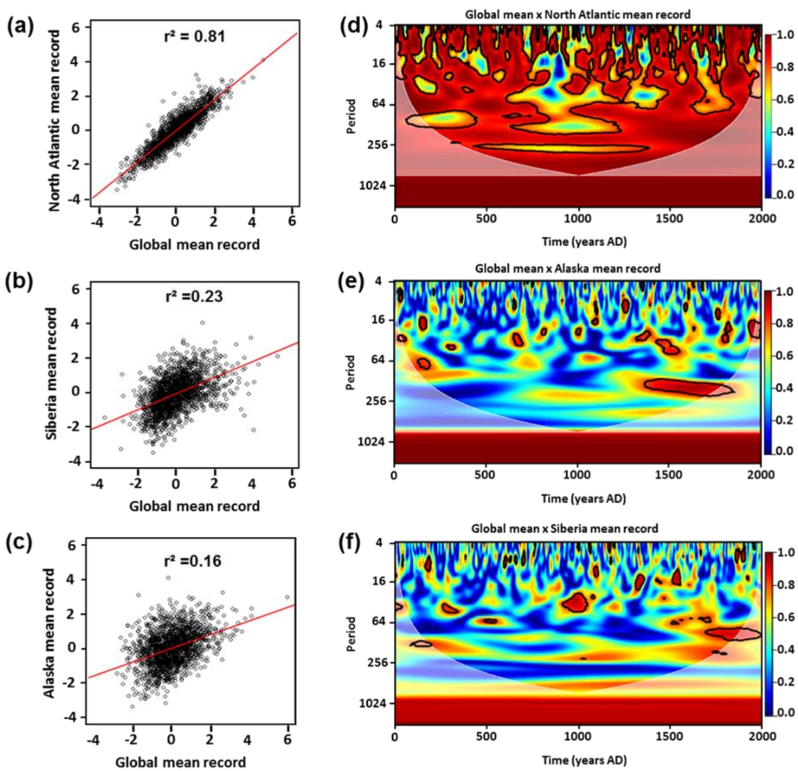



**Figure 3.** Global Arctic mean record obtained from the paleoclimate series contained in the PAGES Arctic 2k database.

**Commenté [NA11]:** Added to precise concerning the way of grouping the data into three groups. The regional approach is now explain by the spatial distribution of the serie and the groupping is confirmed by actual regional climatic influence - Comments (1), (2) and (3) - Referee#1




<u>**Figure 4.** *Left.* Correlation between the global mean based on proxy data and the three regional mean records for (a) North Atlantic (b) Alaska and (c) Siberia areas. Correlations is significant at the 95% confidence level. *Right.* (e) Wavelet coherence between global and North Atlantic mean records, (f) global and Alaska mean records, (g) global and Siberia mean records. Colors represent the amplitude of the signal at given time and spectral period (red equals highest power, blue lowest). White line corresponds to cone of influence on wavelet coherence spectrum. Confidence level of 95% (α=0.05) is indicated on wavelet spectrum with the black line.</u>

**Commenté [NA12]: Developed to precise concerning the way of grouping the data into three groups. The regional approach is now explain by the spatial distribution of the serie and the groupping is confirmed by actual regional climatic influence - Comments (1), (2) and (3) - Referee#1**

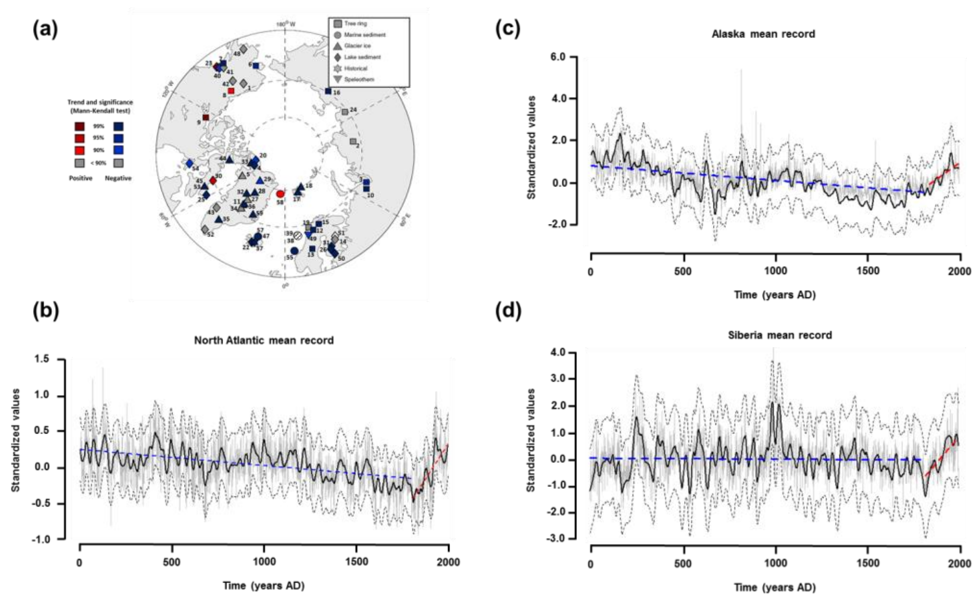



**Figure ~~3~~5.** (a) Individual trends for each records before recent warming. White dot highlighted inconsistency between two tendencies for the same archive. North Atlantic (b), Alaska (c) and Siberia (d) regional 50-years LOESS. Blue colors indicate decreasing tendency whereas red colors indicate increasing trends. Dashed black lines correspond to the 95% confidence interval.

**Commenté [NA13]:** Confidence interval were add to judge the significance of the LOESS-filtering and the trend – Referee #2

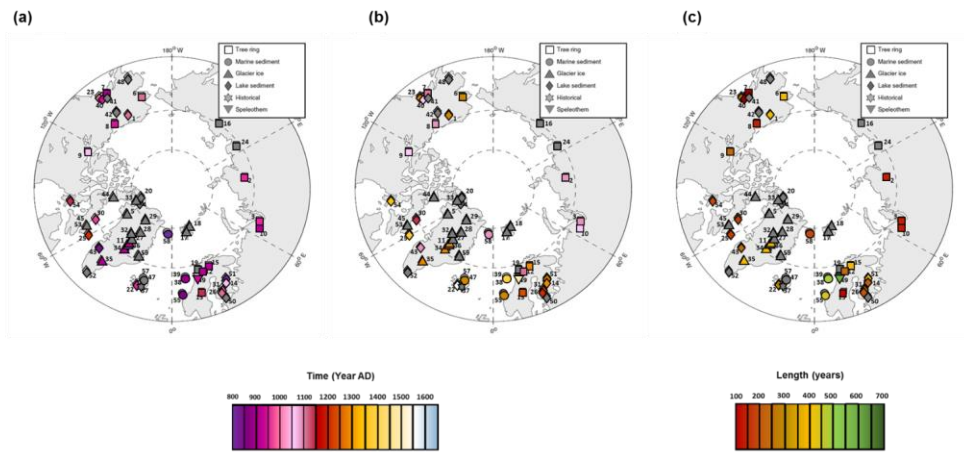



**Figure 6.** Expression of the Medieval Climate Anomaly (MCA) of the Arctic 2k series based on references paper (see McKay and Kaufman, 2014): starting (a), ending (b) and length (c). Symbols in grey correspond to series for which the MCA is not mentioned by the authors. More details concerning the temporal expression of the LIA are available in Table S4 and Figure S2.

**Commenté [NA14]:** Added to also describe the expression of the warm MCA in the Arctic area – Referee #3

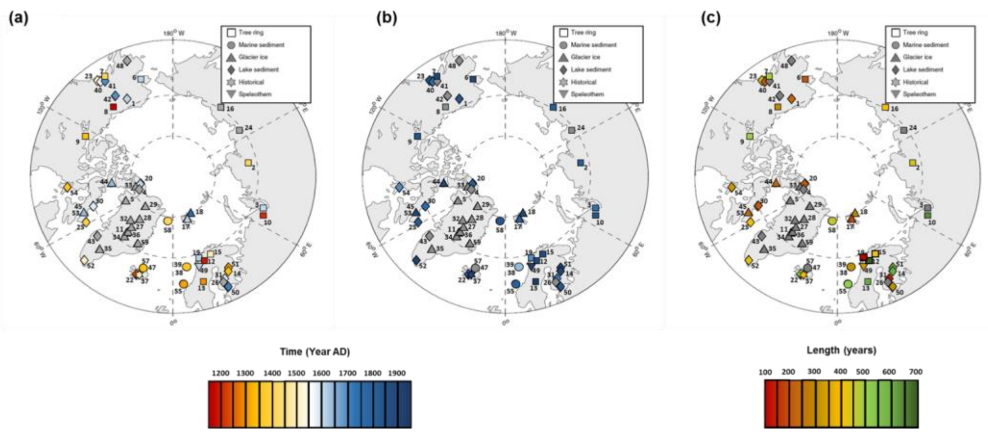



**Figure ~~4~~7.** Spatial expression of the Little Ice Age (LIA) of the Arctic 2k series based on references paper (see McKay and Kaufman, 2014): starting (a), ending (b) and length (c). Symbols in grey correspond to series for which the LIA is not mentioned by the authors in the original publication. More details concerning the temporal expression of the LIA are available in Table S3 and Figure S1.

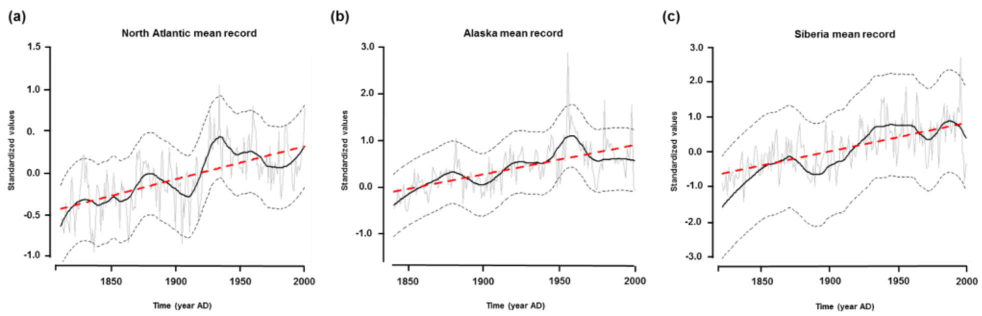
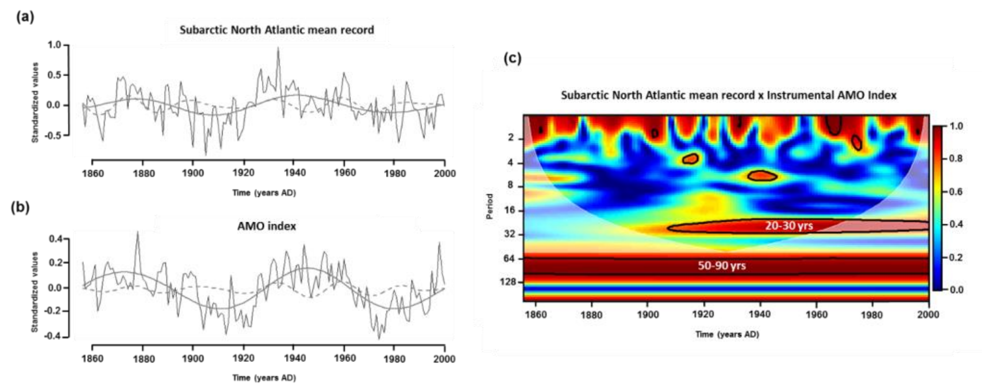



**Figure ~~5~~8.** Regional mean records of the last two century showing the recent warming period Red dashed lines correspond to linear trend obtained from Mann-Kendall test and black curve to ~50-years loess filtering. Dashed lines correspond to the 95% confidence level interval.

**Commenté [NA15]:** Confidence interval were add to judge the significance of the LOESS-filtering and the trend – Referee #2



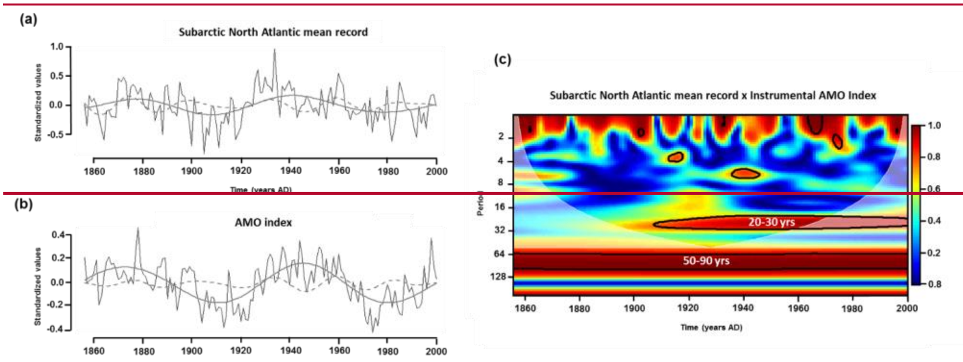




**Figure ~~6.~~9.** Wavelet coherence analysis between subarctic North Atlantic mean record and instrumental AMO index during the 1856-2000 AD period. (a) Subarctic North Atlantic mean record (this study) and (b) instrumental AMO index (Enfield et al., 2001). Grey lines and dashed lines corresponds to 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.

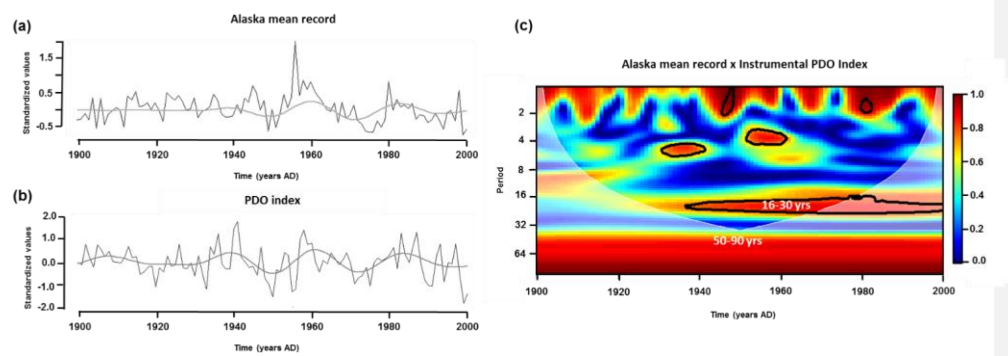



**Figure ~~8~~10.** Wavelet coherence analysis between Alaska mean record and instrumental PDO index during the 1900-2000 AD period. (a) Alaska mean record (this study) and (b) instrumental PDO index (Mantua et al., 1997). Grey lines corresponds to filtered and wavelet reconstructed of the ~16-30 years 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.

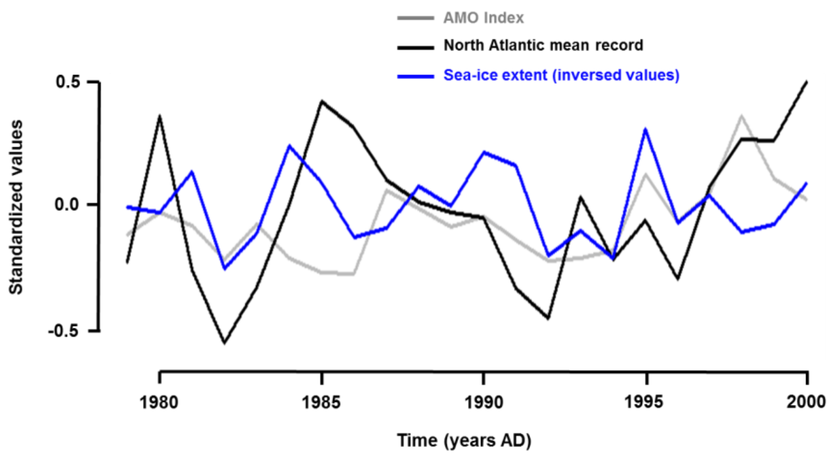
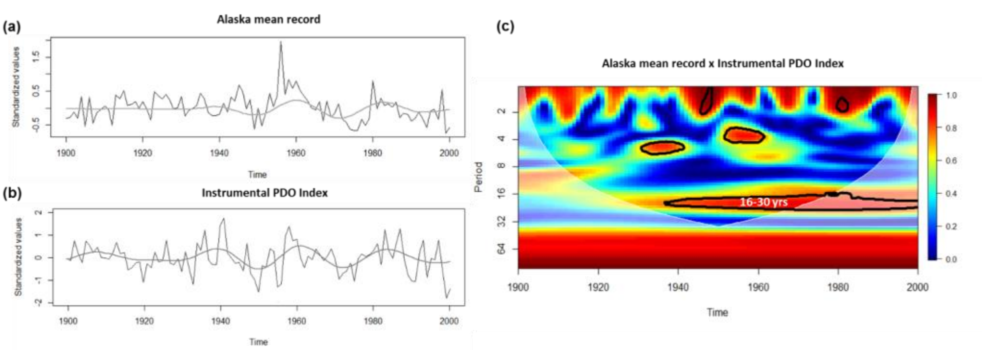



**Figure 11.** Comparison between the North Atlantic mean record based on proxy data, the AMO index and the global Arctic sea-ice extent during their common period (1978-2000).

~~**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% ($\alpha$=0.05) is indicated with the black line.**~~