Response File – Climate of the Past Manuscript cp-2017-34

We thank the reviewers for their time reviewing our manuscript and their insightful comments and suggestions.

Below we provide the original responses to each of the reviewers' comments that indicated our plans to revise the manuscript and subsequently the specific changes that we have made to the revised manuscript. Reviewer comments are shown in *italic*. Our original responses are shown in **bold** and the updated descriptions of how we have revised the manuscript are shown in **bold blue text**. Quotations from the original manuscript are shown in ***bold italics*** and quotations from the revised manuscript are shown in ***bold blue italics***.

Reviewer #1

The overall quality of the discussion paper "Arctic hydroclimate variability during the last 2000 years – current understanding and research challenges" intended for the Special Issue "Climate of the past 2000 years: global and regional syntheses", is good. The manuscript presents a substantial, thorough, and updated contribution on hydroclimate variability during the past 2 ka in the Arctic. The concepts, ideas, methods, and data from different climate archives are clearly presented. The results are discussed in an appropriate and balanced way, including appropriate references. The scientific results and conclusions are presented in a clear, concise, and well structured way. The number and quality of figures and tables are appropriate, as well as the English language.

We thank the reviewer for these encouraging comments.

Specific comment: Please note that Lake Nerfloen listed in Table 2 is located in western Norway, not Northern (N) Norway.

This has been corrected in the revised version. Done

Reviewer #2

This paper attempts to provide a synthesis of palaeoclimate records spanning the last 2000 years in the Arctic region. In general, the content and subject matter are important and certainly well suited to Climates of the Past. However, prior to publication, I strongly recommend the authors undergo major revisions and resubmit their manuscript for further review.

We thank the reviewer for her/his detailed examination of our manuscript and the very insightful comments. It seems that the reviewer has possibly misunderstood the purpose of this paper, which is being a review paper, aiming at highlighting the methods used to investigate hydroclimate variability in the Arctic region, as well as providing an overview of existing understanding of it. If this is unclear, we will make sure to highlight it in both the abstract and introduction of the revised version.

We have now emphasised that this is a review paper, both in the abstract and in the introduction (see below).

Major comments

The content of this paper performs two broad functions. The first 23 pages provide a brief background to Arctic climate research, followed by a long review of the techniques used to infer past climate variability in the Arctic. The second part of the paper consists of a synthesis of published hydroclimate reconstructions and model hindcasts for the region, spanning the last 2000 years. The paper's title and abstract only refer to the second component (the synthesis), thus the extremely long introductory review comes as some surprise. As a first step, I suggest that the authors consider cutting the paper in half and creating (1) a review of palaeoclimate techniques applied to the Arctic, and (2) a synthesis of the palaeoclimate data. With respect to (1), the authors must carefully consider whether this would represent a valuable addition to the literature beyond the several books and review papers on palaeoclimate techniques. However, in order to meet the objective described in the abstract, this paper needs to be shorter and more focused on the data synthesis.

As stated above, this paper is not a research article, but a review article. The reviewer is right that the various methods used are described elsewhere in the literature, but, as far as we know, not collectively, with an Arctic focus. Our aim with this review paper is to provide a holistic understanding of the complexity of attempting to infer past hydroclimate variability across the whole Arctic (and even at single sites). To achieve that aim, the archives as well as methods need to be described, and examples of hydroclimate inferences given. Consequently, this article could be seen as a "mini textbook" of Arctic palaeohydroclimate. Thus, in that respect, dividing this paper into two separate papers would be not meaningful. However, we will focus the "introductory review", i.e. the archive description part, better in the revised version.

We have emphasised that this is a review in both the abstract:

"The aim of this review is to summarise the current understanding of Arctic hydroclimate during the past 2000 years. First, this paper reviews the main natural archives and proxies used to infer past hydroclimate variations in this remote region, and outlines the difficulty of disentangling the temperature from the moisture signal in these records. Second, a comparison of two sets of hydroclimate records covering the Common Era from two data-rich regions, North America and Fennoscandia, reveals inter- and intra-regional differences. Third, building on earlier work, this paper shows the potential for providing a high-resolution hydroclimate reconstruction for the Arctic and a comparison with last-millennium simulations from fully-coupled climate models.".

…" Finally, this review illustrates that the proxy data regional coverage is inadequate, with distinct data gaps in most of Eurasia and parts of North America, making robust assessments for the whole Arctic impossible at the present. Given the heterogeneity of Arctic hydroclimate variations, we recommend detailed regional studies, rather than the entire Arctic region."

and in the introduction:

The aim of this review is to summarise the current understanding of Arctic hydroclimate, focusing on the last two millennia. The paper uses the PAGES 2k definition of the Arctic, i.e. the region north of 60°N. Section 2, briefly presents the current state and a future outlook of Arctic hydroclimate and impacts, from observations and climate model

simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al., 2012). Section 3 reviews the various archives and proxies used to derive information on past hydroclimate variability. Section 4 presents multiproxy comparisons of hydroclimate variability in Arctic Canada and Fennoscandia, two regions with denser networks of sites. In section 5, a new compilation of Arctic hydroclimate data, which illustrates the potential to derive higher temporal resolution than that of Ljungqvist et al. (2016), is compared to model simulations from the third Paleoclimate Modelling Intercomparison Project Phase III (PMIP3, Braconnot et al., 2012). The current understanding of Arctic hydroclimate during the last 2k is summarized in section 6, and some recommendations for future work are given in section 7.

We have also tried to streamline (shorten and sharpen) the text to make it more readable, as well as adding some additional relevant references.

With respect to the palaeoclimate synthesis, this section warrants a more detailed and systematic approach than is provided in the current manuscript. This systematic approach should include reverting to a more traditional journal article format, with an introduction, methods, results and discussion. As a minimum, the methods section should provide a clear and detailed description of the process of identifying and screening the published records for the Arctic region, which is not satisfactorily clear. The results section should detail which records were considered, how many were included/excluded and for what reasons. The PAGES 2k network have provided very clear guidelines for this process, and the screening process is described briefly on pages 27-28, however a detailed description and summary is necessary in order for readers to appreciate how comprehensive the search has been. For example, are all records described here included in Ljungqvist et al. (2016)? If not, which additional records were included, and which were excluded?

Furthermore, the approach to deriving the new hydroclimate proxy synthesis, described perfunctorily on page 28, requires a much more detailed description and appraisal as is afforded here. In this respect, I have several questions which are not answered in the manuscript: (1) How was the age uncertainty in these records dealt with when de- riving averages for the multiple records?; (2) How were the timesteps aligned in order to derive an average of the multiple records? Was this by linear interpolation or another approach? Were the data smoothed in any way, or binned? (3) The synthesis contains records that have an average sample resolution of <50 years, yet the resulting timeseries suggests variability at much higher frequencies – how is this possible? Is the synthesis weighted more heavily towards the annually resolved records? (4) The spatial coverage of records used is uneven, with certain regions being more heavily sampled than others. Of note, for example, are the several Greenland ice core records are included in the synthesis. How does the regional synthesis deal with the bias towards those heavily replicated regions? (5) Finally – I would argue it is misleading to state that the results generated here are 'not a reconstruction'. True, the hydroclimate timeseries isn't calibrated against a particular climate signal, however it is a qualitative reconstruction of relative hydroclimate variability in the Arctic. Generally speaking, given the proliferation of numerical approaches to deriving regional and global syntheses of time-uncertain palaeoclimate records (see for example Anchukaitis and Tierney, 2012, Climate Dynamics), there is considerable un-realised potential in this research that could (and should) be investigated in more detail. If more involved numerical approaches are deemed unsuitable, then some justification as to why must be given.

The aim of this particular exercise was to show the potential to derive higher-resolution hydroclimate information than provided by Ljunqvist et al. (centennial). See also the comments by Ljungqvist on this manuscript. It is clear that the synthesis is biased, and this is partly the point: showing the uneven spatial representation leading to biases if the aim is to represent the whole Arctic.

Moreover, since at this point we do not intend to make a stand alone paper of the synthesis, we will not go into too many details here. Still, we will follow the reviewers' recommendations regarding clarification of methods and data used in the revised version. We do however, hope that a more thorough attempt to reconstruct past Arctic hydroclimate variability will be made as new records emerge. Hopefully, our paper can serve as an inspiration to that.

The hydroclimatic record corresponds to an average of all the series used. It was calculated taking into account the different time step of the series used (2). The resulting mean record suggest high frequency variability because it corresponds to a year per year average. Since all series are not at the annual resolution, a curve of the number of series per year has been added. It will be able to determine the temporal representatively of the regional mean record (4). Because several records have an average sample resolution > 50 years, the frequency variability inferior of this time step were not interpreted (3).

In the revised version, the description of the compilation has been changed, highlighting our intent to make a qualitative compilation of some of the available and previously used data. There are two main messages: 1) it is possible to get more high-resolution variability than provided by L16, which will slightly alter the composite hydroclimate evolution through time (e.g. Fig. 13), and 2) This particular composite (and indeed that from Ljungqvist et al.) is biased towards the data-rich North Atlantic sector. It is quite clear that none of these two "compilations" actually represents the whole Arctic. However, during the process of putting together this review more data has become available (e.g. Fennoscandia) and if more data become available (N America and Russia) there will be potentials for reconstructions with better whole-Arctic representation. Nevertheless, this is not the scope of this review.

Related to the review of regional palaeoclimate records, I found the multiple plots of palaeoclimate timeseries (Figures 7-11) quite unhelpful, not least due to the variety of ways the data are plotted (including the use of various graphical styles and time axes being both vertical and horizontal). It would be much more helpful to view a smaller selection of these records in a single figure (maximum two if necessary) on a common timescale in order to assess the Arctic-wide synchronicity or otherwise. It would also be helpful to view the regional synthesis timeseries in comparison with the records from which it was derived, so the reader can get a feel for how certain records have influenced the synthesis.

The figures are intended to highlight the nature of the regional hydroclimate information gained from different proxies (Figs. 7-10), as well as a regional comparison of a variety of hydroclimate proxies with different resolution (Fig. 11) in a review context. It would be possible to compile these into one of two figures, but we feel that this would be less meaningful. As, the figures are intended to highlight the various Arctic hydroclimate archives, and consequently we feel that it is better to show these as

they are usually depicted. Thus, unless the editor objects, we will keep the figures as they are.

As above.

Parts of the manuscript read well, however I would advise the authors ask a native English speaker to proof-read the manuscript before resubmission.

We will do that given the opportunity to revise the manuscript.

The native English speaking co-authors have now gone through the manuscript in detail

Minor comments

Abstract: The abstract describes 'inadequate proxy data coverage' (Page 1, Line 37), yet then goes on to call for 'detailed regional studies, e.g. including field reconstructions'

Yes, given the large regional hydroclimate differences within the Arctic, it would be more useful to focus on those regions that are presently well replicated rather than attempting a whole Arctic study, which would be regionally biased. We will clarify that in the revised version.

We have changed the last sentences to: *Finally, this review illustrates that the proxy data regional coverage is inadequate, with distinct data gaps in most of Eurasia and parts of North America, making robust assessments for the whole Arctic impossible at the present. Given the heterogeneity of Arctic hydroclimate variations, we recommend detailed regional studies, rather than the entire Arctic region. Also, field reconstructions are useful to disentangle spatial patterns and potential forcing factors. However, at present, it is only possible to carry out regional syntheses for a few regions, e.g. Fennoscandia, Greenland and western North America. To fully assess pan-Arctic hydroclimate variability for the last two millennia additional proxy records are required.*

(P2, L3). How is the latter possible if there's inadequate data?

See above comment.

We hope that this is clearer now.

Section 2.2.1: I'm not entirely sure this section is necessary for this paper.

Since this is a review paper, we feel that also mentioning the potential future impacts of hydroclimate changes are important to acknowledge, i.e. connecting the past to the future.

We kept this section

P4,L25: the Arctic's. Errors related to the articles (misuse or non-use of the and/or a) *are frequent throughout the manuscript.*

Thanks, this will be corrected throughout. Done

P5,L18: ‘there are’, not ‘there is’; ‘phenomenon, which also: : :’

Corrected. Done

P6,L7: This sentence could be worded better – e.g.

???

Sentence changed to: ***Hence, their ages, and the potential lengths of the records they contain, are diverse across the Arctic, ranging from the entire Holocene in Beringia and Scandinavia, to a few hundred years in Greenland or Iceland.***

P24,L11: ‘extensive’ -> ‘extensively’

Corrected. Done

P24, L11: ‘Typically annual precipitation: : : have been the targets’. This is not a complete sentence.

This has been changed to: ***Typically annual precipitation, along with temperature, or lake levels have been the targets for reconstructions***

P24, L15: ‘Although potentially: : :’ Also not a complete sentence, and what is meant b the records not being available – not published?

Yes, this is an awkward sentence, which will be revised. Also, networks of these are not yet available. We revised the sentence as follows: ***Presently, there are few published hydroclimate reconstructions using other proxies, although these proxies have the potential to produce records with high temporal resolution. However, networks of these are not yet available.***

P24, L20: ‘Towards the west’. The spatial context is very vague here – do you mean western Canada?

Revised as follows: ***In western Canada and Alaska, there was an increase in precipitation during the past 2000 years, whereas a long-term decrease was seen towards the east.***

P24, L20: ‘there seems to be’. Use of present tense. In next line, past tense is used. Ensure there’s a consistent approach to tense (ideally use past when discussing past events) throughout.

Thanks, this will be corrected throughout: Done

P24, L23: ‘All show: : :’ What shows? Maybe better link up to previous sentence.

Thanks, we will change to “They all show…” Done

P24, L26: 'Several'. Be more specific here when reviewing records. How many have been published?

In this context we do not feel that it is not necessary to give the exact number since many of these are from locations below 60N, i.e. outside the PAGES 2k Arctic limit. The idea is to highlight the tradition of paleohydrological studies in this region, but if this is unclear, we will re-formulate this sentence in the revised version.

Changed text in the revised version: ***In Fennoscandia, ~~several~~ palaeolimnological studies have recently produced records indicative of past regional hydroclimatic variability. ~~These~~ Such records are based on micro-, macro- and megafossil assemblages, in addition to lithological data. Here we use sixteen palaeolimnological records from the Arctic region (Table 2, Fig. 11) to illustrate hydroclimatic shifts and variations in Fennoscandia over the Common Era***

P24, L27: 'These..' merge with previous sentence.

Corrected. Done

P25, L9: 'A visual inspection: : :' As described above, it would be preferable to summarise what records exist before identifying those relevant to this synthesis.

These are the presently available records containing hydroclimate information from the Arctic part of Fennoscandia (see above) and they are presented in Table 2. We will revise this sentence so that this is clear.

A visual inspection *of the records shown in Fig. 11…*

P26, L25: By this point, it would be useful to refer to a figure with some data.

They are shown in Fig 11, but we will refer to that figure in this sentence. See above

P27, L16: 'variability' typo

Corrected Done

P27, L18: 'method outlined below'. As described above, it would be better to outline this in a proper methods section.

See comments above

We have now stressed that we are making a synthesis (qualitative rather than quantitative): *"Here a new synthesis of Arctic hydroclimate variability extending back to 800 CE is performed, utilizing both high-and low-resolution records. Note that this is not a quantitative reconstruction, but only provides a qualitative view of relative hydroclimate variability in the Arctic. The aim is to assess the potential to derive an Arctic hydroclimate record with more high-frequency information than that derived for the same region from the results of Ljungqvist et al. (2016)"*

P28, first paragraph. As above, put this in the methods.

See comments above

We have rearranged the text in the paragraphs describing the methods used so that it makes more sense to the reader.

P28, L6: What is meant by 'even more important'?

This sentence has been changed to *"This drastic selection is necessary to allow for comparison of data at centennial scales and facilitates the time series analyses"*

These strict selection criteria are necessary to allow for comparison of data at centennial scales and facilitate time series analysis

P28, L9: What is meant be 'e.g. tendencies'

This sentence has been changed to *"… offer the possibility to interpret hydroclimate variability in the Arctic from low to high frequencies."*

P28, L17: 'This signal is not a signal of precipitations' This sentence needs some attention.

This sentence has been changed to *"This is not a signal of precipitation alone, but most likely combination of all processes related to the hydrological cycle"* Done

P28, L22: The value of the Mann-Kendall test is not clear in this context.

We think that the reason for using the M-K test is clearly stated (if that is what is referred to by the reviewer?)

The M-K test was used to analyse the long-term trends in the records

P29, L3: Wavelet description. Unless you are using a non-standard wavelet package, I don't think it's necessary to provide such detail. That said, wavelet analyses are notoriously susceptible to errors related to unevenly spaced data – was this considered in your analysis?

Agreed, the revised description of the wavelet will be less detailed. Done

P29, L16: 'To minimise the impact of the 1456-1485 CE event': : : Please provide more justification as to why it was necessary to filter out this event, and on the effects of that decision.

This will be added to the revised version.

In the revision we state: *"Because wavelet analysis is sensitive to large events that may hide the lowest frequencies recorded, the 1456-1485 CE event was extracted by wavelet filtering and the signal reconstructed by inverse Fourier transform before using CWT.*

P29, L20: Comparing the North Atlantic and Alaskan records to the 'global' analysis, which constitutes both regions. This (as far as I can tell) is a flawed comparison, since surely the North Atlantic subset will be most similar to the global record, since 12 of the 17 constituent records are from the North Atlantic.

Yes, that is completely true and also the reason form this exercise, as described in the opening sentence of this section. However, given appearances of the time series for the two regions (Fig. 16) in comparison to the "global" one (Fig. 14), this is already quite evident. We will remove Fig. 17 and briefly mention this in the revised text.

Figure 17 was removed

P30, paragraph 2. Comparing models with palaeoclimate data. This is a very brief and one-dimensional comparison given the importance of models for future projection. Much more detail should be provided on the similarities/differences and what that means for either the validity of the models or the palaeo- data.

We agree that the one-dimensional comparison is brief, but spatial patterns and their temporal evolution over the past time is the main and the most important information that a grid reconstruction can convey. We therefore compared the similarities/differences of the temporal evaluation between MCA and LIA in both the grid reconstruction and the model simulations. We then discussed the possible reasons that could cause the discrepancy of the different expression on the temporal evolution between the reconstruction and the models.

We have made some changes on this section, partly based on the new figure 12, including a statement regarding the comparison of differences in proxies and models across the MCA-LIA: *Caution needs to be advised, since the magnitudes of the differences in proxy-derived hydroclimate between the MCA and LIA is consistently larger than in the model ensemble mean or in the individual model simulations. However, the discrepancy between models and proxies may imply that the changes in spatial hydroclimate patterns from the MCA to the LIA over Fennoscandia and Greenland are not related to changes in external forcings, but possibly by internal variability.*

However, given the scope of the paper, as well as the scarceness of the proxy data, we don't want to elaborate too much on this topic, which is clearly worth a study of its own.

P30, L30. At some point you need to justify why this new synthesis is an improvement on than L16, or indeed why it is necessary beyond L16.

It is difficult to say which synthesis is better. However, the new synthesis shows a shorter period of wet anomalies during the MCA, and the variance is much larger after ca 1200 CE. Given high heterogeneity of the spatial patterns of precipitation, the new synthesis provides a new hypothesis of the temporal evolution of the arctic precipitation after ca 1200 CE.

Moreover, it is clear that the new synthesis much more variability at centennial timescales after ca 1500 CE than L16, which is more in lie with the model ensemble mean. A brief comment on this has been added to section 6.2: *At least from the LIA and*

onwards, there is a better agreement between the model ensemble mean and the new synthesis than with L16. Both Arctic hydroclimate records derived from L16 and the composite presented here are, however, insufficient for drawing any firm conclusions for the whole region.

P31, L25: 'Quite flat' – a more scientific term could be used here.

Agreed, the sentence will be changed to "This is in agreement with L16, albeit the new Arctic mean displays more variability during the LIA than L16"

Changed to: *The new Arctic hydroclimate mean synthesis (Fig 13) suggests drying during the MCA, but wet conditions in the early part of the LIA and drier conditions in the latter part. This is largely in agreement with L16, although the latter shows less variability during the mainly dry LIA*

P31, L26-27: I fail to see why the absence of calibration for the new record would have any effect on the trend or variability within the record. The units and range would change, but the pattern would be identical before and after calibration.

Depending on the trends of the included records, this could have a distinct impact on the reconstruction when fitted to observations during the calibration period. Yes

P32, L1: 'not fully capturing the observed changes in the latter half of the 20th century'. Have you considered that other (non-climate) anthropogenic activities, such as recovery from acid rain, nutrient deposition or other atmospheric transport of pollutants may have influenced the recent signal in some proxies?

Good point, this will be added to the revised version

We removed this part of the text during the revision

P32, L12: 'this period did possibly undergo'. Mixed up nouns and verbs in this sentence – need to re-word.

Corrected: *"… this ~~period~~ was possibly ~~undergo~~ a period of noticeable climatic fluctuations."*

P32, L19: The paragraph on seasonal effects would be better merged into the proceeding text and not afforded a separate subheading.

OK, changed Done

P33, L3: change 'unbalance' -> 'imbalance'

Corrected Done

P33, L9: Here you list future recommendations. Why not include these ideas in the bullet points listed below?

Good point, thanks.

Actually, this is recommended in bullet point 3 (now 4): *Consolidate data, and even attempt to make a field reconstruction, for regions with sufficient number of hydroclimate proxy records in time and space. Presently there seems to be opportunities for a cross-Atlantic study, which may shed light onto observed regional hydroclimate patterns and the mechanisms behind those*

P33, L15: Bullet point 1 is two points. Also, by listing all records identified and screened in the results section, you would clearly make the point about data suitability and availability.

Good point, thanks.

- ***Increase the spatial coverage of hydroclimate proxies. This is particularly important for Eurasia (except Fennoscandia), but especially North America.***
- ***There are several hydroclimate records that would add valuable information which are not publicly available, so it is important to encourage palaeoclimate researchers to share their data.***

Still, we don't feel that there is a need to again list the suitable/available records in this section. We do note, however, that in connection with this review, several new records have been made available: *It is encouraging that several new hydroclimate records have been made available during the process of preparing this review (see Table 2)*

P33, L19: 'Proper Arctic2k hydro database. I thought this was the point of this paper?

No, no such dedicated data base does yet exist. **We do hope that this review paper can lead to the creation of such a dedicated data base.**

P33, L23: 'Field reconstruction' – I got the feeling from reading this paper that a field reconstruction isn't really feasible due to a lack of spatial data coverage.

There are potentials for some regions with good data coverage, e.g. Fennoscandia and parts of N America and possibly Greenland. But it is not possible for the whole Arctic.

This is stated in section 6.2: *However, due to the low number of available hydroclimate proxy records from the Arctic, and the imbalance in spatial coverage (Table 3, Fig. 12), it is currently impossible to prepare a field reconstruction for the whole region.*

P33, L25: Better collaboration between modellers and palaeo-data collectors is often called for. Can you be more specific as to what the two disciplines could do to improve collaboration?

We will elaborate in the revised version

Since there is a paper in this CP special issue dedicated to comparison of proxy and model estimates of hydroclimate variability, we refer to that paper rather than adding

too much text to this particular bullet point: ***Closer collaboration with the palaeoclimate modelling community. From the comparison between the existing "observational" data (reanalysis and proxies) and climate model simulations, discrepancies as well as similarities in both rate and spatial distribution were evident, and this needs to be addressed (Smerdon et al. 2017).***

Tables 1 and 2: Why do we need two tables here? Why not merge? Also, are these all the published records from the Arctic, or just those you could access?

We want to keep them separate because table 1 represents the data available for Fennoscandia and Table 2 the data used in the synthesis. These data are those that are available.

We have now added a table presenting the N American data (Table 1). Table 2 describes the Fennoscandian data, and 3 the data for the synthesis.

Table 3: this is unnecessary. Just indicate which records are used in table 2.

Agreed. Done (used record are given in bold in new table 3)

Figures 1-5. Five figures here is too many. Boil them down to one or 2 most important.

We have replaced Fig. 1 by Fig. 3, and put Fig. 2, 4 and 5 together as Fig. 2. Done

Figures 7-11. See comment above.

See comments above OK

Figures 12-13. Merge these figures to 1.

Agreed. Done (new figure 8)

Figure 17. What are the red lines here? Best fit lines? If so, they don't appear to bisect the data as would be expected. Perhaps there's an issue?

Fig. 17 will be removed (see response above). Done

Figure 18. It would be useful to map z scores, as is the case in the final synthesis. Also, I fear you may be over-interpreting the scale of the yellow-green change in Greenland in Fig. 18a – the range is just 0.2 hydroclimate index units (also explain what that unit actually is).

Good point, we will map the z-scores instead.

We mapped the z-scores and also revised the interpretation of the proxy-based Greenland precipitation

Figure 20. I'm not sure this figure is necessary.

Seasonality is an important issue in paleo climate reconstruction, since the archives may contain hydroclimate information for different seasons. So we chose to keep this figure.

Figure 20 (now Fig. 14) is kept.

Data review team

Essential additions for this paper:

(1) Table 1: Add Data Citations for all of the proxy datasets listed in this table and shown in Fig 11. For those data not already in a public repository, submit essential metadata and data, and add the corresponding Data Citations.

In the updated version of the manuscript, "Data citations" will be added with the Data URL for the series used in this study.

This has now been done in new tables 1 (North America) and 2 (former table 1: Fennoscandia). Note that one dataset is not yet accessible due to the PI being out on an oceanographic expedition. The record will, however, be uploaded as soon as she returns ashore.

(2) Table 2: List the proxy climate time series shown in Figs 8, 9, and 10, along with a corresponding Data Citations. Add the original publication citations for each record in Table 2 (like in Table 1).

In the updated version of the manuscript, "Data citations" will be added with the Data URL for the series used in this study.

The data in Fig 4 (old Fig. 8) is already in Table 2 (Gunnarson 2008 + URL), but we have added the link to the figure caption. Data citations for N American data in Figs. 5-6 (old figs. 9-10 is) are in the new table 1.

(3) Submit the time series of the resulting hydroclimate composites (Figs 14, 16 and 19) for archival and include the data citation.

The regional curves obtained will be published online after the publication of this article.

The curves are now available online: https://figshare.com/articles/Global_North_Atlantic_Alaska_synthesis_record_txt/5502199

Possibly essential, depending on source of the data:

(4) If the data shown in Fig 6 are based on chronologies already archived and easily accessible in the ITRDB, then all is well. If instead the chronologies from the ITRDB were detrended or otherwise modified by the authors, then those new chronologies must be submitted for archival as part of this study. Either way, please clarify the data methods used to create Fig 6.

We will clarify the methods used to standardise the tree-ring data used in Fig.6 as follows: "The biologically induced age trend was removed from the TRW data through standardization with a cubic-smoothing spline with a 50% frequency cutoff at 35 years (Cook and Peters, 1981). This detrending preserves annual to decadal scale variations in the detrended tree-ring data. The resulting dimensionless indices were arithmetically

averaged into single site chronologies. Variance changes arising from changes in sample replication over time were corrected (Frank et al., 2007). Resulting chronologies were truncated where the sample size dropped below 5 trees".

Since the chronologies standardised using the above described method are presently being used in another study, the standardised chronologies will not be archived until that study is finished. However, since free software and code to standardise tree-ring data are freely available, given this description the data used here are easily recreated. It should also be noted that the method of standardisation used depends on the purpose of the study and the tree-ring data itself, so the tree-ring data set described in this study is just one of many potential versions of it.

Given the brief discussion related to Fig. 6, and that this information has previously been published, we have now omitted figure 6 and instead refer to St George and Ault 2014 (see their Fig. 1) which basically provides the same information.

Recommended:
(5) Contrary to what is shown in Table 2, many of the records appear to have been taken from Ljungqvist et al.'s global compilation. Essential metadata that are needed for intelligent reuse of the data in new synthesis are missing from the Ljungqvist et al. compilation, which undermines a primary goal of the PAGES data stewardship activity. We strongly encourage the authors to use the opportunity of this synthesis paper to start with the original datasets and to submit a more complete set of metadata for archival. We note that the Ljungqvist et al. dataset is truncated at 850 AD (the time frame considered in their study). For the current study, the full time series should be used and archived.

The used of Ljungqvist et al.'s series was chosen to access to a high resolution hydroclimate composite for the Arctic. A more complete set of metadata of the serie used will be added in the new version of the manuscript and will include: location, archive type, proxy measurement, dating control, time cover but also original reference and data citation. Even if the dataset is truncated at 850 AD, it is sufficient to have an overview of the expression of the major climatic period that occurs during the last two millennium (i.e. the Medieval Climate Anomaly (950-1250 AD) and the Little Ice Age (1450-1850 AD)).

We keep the time frame given that this exercise is to show the potential of deriving a reconstruction with higher resolution than L16. Still, it is clear that such a reconstruction will not represent the full Arctic: when more data becomes available this will more likely be feasible. The original data sources are now given, as well as data availability. Moreover, the new composites are also available (see above).

Fredrik Charpentier Ljungqvist's comments
This is a very well written – and very timely and important – article that I hope will be published speedily after only minor revision. It serves both as an excellent review article of the state-of-the-art knowledge about the hydroclimate signal in various hydroclimate proxy records from the Arctic/sub-Arctic region and at the same time presents new important findings leading the research forward. Because the article to a considerable extent discusses a recent article of mine (Ljungqvist et al. 2016), I have read it very carefully with great interest and found some minor things that the authors may want to correct or improve prior to final publication.

The article, with new additional proxy records, represents a clear improvement of the understanding of centennial-scale Arctic hydroclimate variability compared to Ljungqvist et al. (2016). The new reconstruction shows more variability during the Little Ice Age. Although this likely partly is because of new additional proxy records it may also be related to slightly different filtering techniques to extract centennial-scale variations.

Thank you for the positive comments and encouragement of the new synthesis presented in our paper.

I have listed my comments below after page number and line number:

Abstract, line 29: To mention the Arctic amplification phenomenon in the introduction to the Abstract seems a bit out of place here in this article devoted to the study of long-term Arctic hydroclimate variations

Given the influence of Arctic amplification on regional hydrology, we do feel that mentioning this already in the beginning of the abstract is appropriate.

Page 2, line 8: It would be clearer to write "anthropogenic greenhouse gas emissions" here instead of the more vague "human activities".

Changed as suggested. Done

Page 2, line 11: Add the reference Hind et al. (2016) to the discussion of Arctic amplification.

Reference added Done

Page 2, lines 29–30: Add Shi et al. (2012) to the list of references here.

Reference added Done

Page 6, lines 8–11: References should be provided to the statement that lake cryosphere has not changed during the past two millennia. I am not so sure that this statement is fully correct, a least not at all locations in the Arctic.

Reference will be provided and statement made more clear.

We changed this sentence to: *The last 2000 years were in general characterized by small glaciers advances, but with regional differences, prior to the general melt of the recent decades (Solomina et al., 2016). This relative stability in surface area over the last two millenia makes lakes excellent recorders of hydroclimate variability for this period.*

Page 6, lines 29–30: These processes are partly dependent on the depth of the active layer. In regions with a depth active layer (e.g. permafrost regions with warm summers) it is less the case.

~~Noted, will be added in the revised version~~.

We have decided not to go into further elaboration on this particular issue, but revised the sentence as follows: ***During summer, the permafrost thaws in its upper part (active layer), leaving sediment easily mobilised by small amounts of rainfall.***

Page 10, line 9: Southern Scandinavia is south of 60N and not in the Arctic. Better to write Central Scandinavia – a region that still is "less harsh" from an Arctic point of view.

Changed as suggested Done

Page 13, line 17: Also cite Borgmark and Wastegård (2008) here.

Reference added Done

Page 14, lines 12–14: Please, double-check the time periods here.

Yes, these will be revised (thanks for noting)

The sentence have now been re-written as follows: ***During the last two millennia, they found generally dry conditions until ca 1600 cal BP (ca.400 CE), varying water tables during the following four centuries, and dry conditions from ca 1200 to 700 cal BP (ca. 800-1300 CE, covering the MCA). The subsequent centuries were again variable, while the period 500-200 cal BP (1500-1800 CE, covering the LIA) was wet and the last two centuries dry except for the very recent years.***

Page 15, lines 24–25: Add the also very relevant references Esper et al. (2002), Schneider et al. (2015), and Stoffel et al. (2016) here.

Reference added Done

Page 15, line 26: Add Shi et al. (2012) to the list of references here.

Reference added Done

Page 17, line 14: Medieval Warm Period/Medieval Climate Anomaly – medieval is too vague and a different meaning (as a time period) in history than as a climate period.

Quite right, a mistake and now changed as suggested Done

Northern Fennoscandian region during the Little Ice Age and Mediaeval period **changed to** ***Northern Fennoscandian region during the LIA and MCA***

Page 18, line 11: Maybe it is worth to mention that a tree-line as high as 73N only occurs in parts of central Siberia (e.g. the Taimyr Peninsula)?

Changed as suggested

Within the Arctic 2k region, trees are naturally constrained to exist below the latitudinal tree line*, extending as far as ca. 73°N in parts of central Siberia,*

Page 22, line 31: "GISP-2" should be written "GISP2".

Yes, changed as suggested Done

Page 22, line 32: "O" in "Ymer O" should be with upper case "O".

Indeed! Changed as suggested Done

Page 23: line 2: Geirsdóttir with "ó".

Changed as suggested Done

Page 25, line 2: Why this two time periods for the MCA and LIA, respectively? Some motivation for the choice of time periods would be good. Most data for Fennoscandia indicates pretty old cold conditions during parts of the 12th century whereas many regions appear to have been rather, or very, warm during the 10th century (which also seems to have been the warmest century of the MCA in the Northern Hemisphere).

Quite right, this will be changed in the revised version.

In the text, we are now not including these time frames but we simply refer to LIA and MCA without any temporal indications.

Page 26, line 29: Add a reference to the new article by Helama et al. (2017) about the DACP here. The reference to Ljungqvist (2009) is wrong here: Ljungqvist is misspelt ("k" instead of "q") and it should be Ljungqvist (2010) – that discusses the DACP – and NOT Ljungqvist (2009) that does not do so.

You are completely right. Helama et al. (2017) added and the right Ljunqqvist paper cited (and so sorry about the misspelling). Done

Page 26, line 30: The word "disturbed" is ambiguous and vague here. It was cold but in what other ways "disturbed" compared to other periods. Larger variability in the climate?

We have rephrased as this: ***Apart from climatic changes related to temperature fluctuations, the DACP was likely a period of marked variable climate conditions.***

Page 27, line 16: The word "variability" is misspelt here.

Corrected Done

Page 28, line 3: "PAGES" should be written with upper case letters (e.g. PAGES and not Pages).

Ooops, changed as suggested Done

Page 29, line 28: Also cite Schmidt et al. (2012) here.

Reference added Done

Line 31, 26: There is an error here: Ljungqvist et al. (2016) does NOT present a calibrated reconstruction. It is an uncalibrated index, ranging from –2 to +2, and with exceeding values truncated to –2 and +2, respectively. All values are standard deviations with respect to the mean of 1000–1899 CE. In some aspects, the approach in Ljungqvist et al. (2016) has some similarities with PDSI and other hydroclimate indices. So, in this respect it is no real differences between Ljungqvist et al. (2016) and the new hydroclimate index in this article.

Response: Thank you for spotting this mistake. We have now amended this in the text.

The sentence "*However, it should be remembered that L16 is a calibrated reconstruction, while the new Arctic hydroclimate record presented here is the average of a compilation of selected series*" was removed from the revised version.

Page 42, line 8. "ans" should be "and".

Changed as suggested Done

Page 61, line 20 (and in numerous citations throughout the article): Weissbach should be Weißbach.

Found the ß symbol, so changed as suggested Done

Arctic hydroclimate variability during the last 2000 years – current understanding and research challenges

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Abstract. Along with Arctic amplification, changes in Arctic hydroclimate have become apparent in recent years. Reanalysis data show an increasing trend in precipitation in the Arctic over the 20th century, but changes are not homogenous across seasons or space. The observed hydroclimate changes are expected to continue, and possibly accelerate, in the coming century, not only affecting pan-Arctic natural ecosystems and human activities, but also lower latitudes through the atmospheric and ocean circulations. However, a lack of spatiotemporal observational data makes reliable quaintification of Arctic hydroclimate change difficult, especially in a long-term context. To understand Arctic hydroclimate, its variability and the mechanism driving it, beyond the instrumental record, climate proxies are needed. The aim of this review is to summarise the current understanding of Arctic hydroclimate during the past 2000 years. First, this paper reviews the main natural archives and proxies used to infer past hydroclimate variations in this remote region, and outlines the difficulty of

disentangling the temperature from the moisture signal in these records. Second, a comparison of two sets of hydroclimate records covering the Common Era from two data-rich regions, North America and Fennoscandia, reveals inter- and intra-regional differences. Third, building on earlier work, this paper shows the potential for providing a high-resolution hydroclimate reconstruction for the Arctic and a comparison with last-millennium simulations from fully-coupled climate models. In general, hydroclimate proxies and models indicate that the Medieval Climate Anomaly was wetter than normal, while the Little Ice Age (LIA) was drier, but it is clear that there are large regional differences. Finally, this review illustrates that the proxy data regional coverage is inadequate, with distinct data gaps in most of Eurasia and parts of North America, making robust assessments for the whole Arctic impossible at the present. Given the heterogeneity of Arctic hydroclimate variations, we recommend detailed regional studies, rather than the entire Arctic region. Also, field reconstructions are useful to disentangle spatial patterns and potential forcing factors. However, at present, it is only possible to carry out regional syntheses for a few regions, e.g. Fennoscandia, Greenland and western North America. To fully assess pan-Arctic hydroclimate variability for the last two millennia additional proxy records are required.

1. Introduction

Global climate is changing rapidly, largely due to increased anthropogenic greenhouse gas emissions (IPCC, 2013). However, distinct regional differences in the magnitude of observed warming in recent decades are apparent, for example, the Arctic has warmed at more than twice the rate of the global average (Cohen et al., 2014). This *Arctic amplification* (Serreze et al., 2009) is due to complex feedback processes within the atmosphere-cryosphere-ocean system, including surface albedo and heat exchange with the ocean (Johannessen et al., 2003; Hind et al. 2016), and has led to substantial losses of sea-ice volume and late-spring snow cover (Overland, 2014).

Increasing temperatures due to global warming lead to an intensified hydrological cycle (Huntington, 2006). Increasing precipitation in the Arctic has been linked to higher local evaporation and reduced sea ice coverage (Bintja and Selten, 2014; Kopec et al., 2016), but also enhanced northward transport of subtropical moisture (Zhang et al., 2013). According to most climate models (see section 2), precipitation will increase in the coming century, with the largest changes occurring over the Arctic Ocean (Bintja and Selten, 2014). However, there are still large uncertainties regarding hydroclimate variability and changes in the hydrological cycle in the Arctic due to incomplete or fragmentary data (Serreze et al., 2000; Screen and Simmonds, 2012). This makes it difficult to detect changes in, as well as understand the mechanisms controlling, hydroclimate variability on different timescales.

There are large spatial differences in the meteorological station density across the Arctic, and except for Fennoscandia and westernmost Russia few observational records reach more than 75 years back in time (Bekryaev et al., 2010), making it difficult to provide a spatiotemporal understanding of hydroclimate variability. Going beyond the observational records, climate proxies are needed. Most reconstructions of past climate for the whole Arctic within the Common Era (CE) have focused on temperature (Overpeck et al., 1997; Kaufman et al., 2009; Shi et al., 2012; Hanhijärvi et al., 2013; McKay and Kaufman, 2014). However, as will be shown here, there are a number of proxies recorded in a few archives, such as ice cores, lake and peat sediments and tree-rings, which can provide information on hydroclimate parameters in the Arctic. They provide information with different temporal and seasonal resolution. In a recent study of hydroclimate variability across the Northern Hemisphere during the last 1200 years, (Ljunqvist et al., 2016) found a tendency for generally wetter conditions during the 9th–11th centuries, corresponding to the Medieval Climate Anomaly (MCA, ca. 900-1150 CE), whereas the 12th–19th centuries, including the Little Ice Age (LIA, ca. 1400-1850 CE) showed more widespread dry condtions. However, for the Arctic, only 18 records with heterogeneous spatial distribution were included. Nevertheless, ongoing efforts to collect new data have resulted in a growing network that will increase our understanding of Arctic hydroclimate variability.

The aim of this review is to summarise the current understanding of Arctic hydroclimate, focusing on the last two millennia. The paper uses the PAGES 2k definition of the Arctic, i.e. the region north of 60°N. Section 2, briefly presents the current state and a future outlook of Arctic hydroclimate and impacts, from observations and climate model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al., 2012). Section 3 reviews the various archives and proxies used to derive information on past hydroclimate variability. Section 4 presents multiproxy comparisons of hydroclimate variability in Arctic Canada and Fennoscandia, two regions with denser networks of sites. In section 5, a new compilation of Arctic hydroclimate data, which illustrates the potential to derive higher temporal resolution than that of Ljungqvist et al. (2016), is compared to model simulations from the third Paleoclimate Modelling Intercomparison Project Phase III (PMIP3, Braconnot et al., 2012). The current understanding of Arctic hydroclimate during the last 2k is summarized in section 6, and some recommendations for future work are given in section 7.

2. Current and future Arctic hydroclimate and its impacts

2.1. Observations and models

Precipitation data derived from the gridded ERA-20C dataset (Poli et al., 2013), averaged over the whole Arctic (≥ 60°N), show a positive trend over the last century, with a notable increase in the last few decades (Fig. 1) in line with previous findings (Serreze et al., 2000; Min et al., 2008). A similar trend is seen in an ensemble of 12 historical CMIP5 simulations (1900-2005, see Table S1 for information on the included models). The spatial pattern of precipitation change is heterogeneous across the region (Fig. 2a and b), with the largest increases in annual precipitation over the North Atlantic and Barents Sea and, to a lesser degree, over eastern Asia, western North America and the North Pacific (Fig. 2a). Annual precipitation decreased in western Eurasia and locally over eastern Greenland and Svalbard. The CMIP5 models show a similar pattern, although the increase is much lower and more spatially homogenous (Fig. 2b), with slightly more prominent increases over parts of the North Atlantic and Barents Sea, and decreases in areas southwest and southeast of Greenland.

For future scenarios, 36 Representative Concentration Pathways (RCP) CMIP5 simulations (12 for each of RCP2.6, RCP4.5 and RCP8.5 scenarios) for the period 2006-2100 were used. Multi-model ensemble means represent robust projections of the temporal variation, spatial patterns and seasonal cycle of the historical and future annual precipitation variability over the Arctic region. All RCPs indicate an increase in mean monthly precipitation in the coming century, ranging from 4 mm (RCP2.6 ensemble mean) to 14 mm (RCP8.5 ensemble mean) (Fig. 1). To obtain the spatial pattern of annual precipitation changes, first the spatial pattern changes were calculated based on individual model simulations, and then re-gridded to the same spatial resolution as the GFDL-CM3 model (i.e. 144 longitudinal grid cells × 90 latitudinal grid cells). The re-gridded spatial pattern changes based on the individual model simulations were then averaged to create a multi-model ensemble mean.

The model ensembles indicate that the most prominent increases in annual precipitation will occur over the Barents Sea, Western Scandinavia, eastern Eurasia and western North America, with decreased precipitation over the central parts of the North Atlantic (Fig. 2c to e). Moreover, the model simulations suggest an intensified precipitation cycle, with increases in all months, but more prominently outside late spring/early summer (Fig. 2f and 2g).

2.2 Impacts of Arctic hydroclimate change

2.2.1. Impacts on Arctic environments

Changes in hydroclimate will have impacts on Arctic terrestrial and marine environments, including the cryosphere and the Arctic Ocean (ACIA, 2005). Observational studies show evidence of increased precipitation and river discharge in the Arctic, and hence a freshening of the Arctic Ocean, over the last decades (e.g. Peterson et al., 2006; Min et al., 2008). The freshening will have impacts on ocean convection in the subarctic seas, influencing the thermohaline circulation (THC, see below) (Min et al., 2008). Increased ocean freshening will also have implications for marine flora and fauna distribution, due to altered light and nutrient conditions (Carmack et al., 2016). Planctonic primary producers are likely to be affected, some positively and some negatively, and these impacts may cascade further up in the food web and alter the whole marine ecosystem structure (Li et al., 2009), affecting marine biodiversity. Overall, changes in landscape and biophysical properties, biogeochemical cycling and chemical transport associated with warmer and wetter conditions will influence ecosystem productivity (e.g. Wrona et al., 2016). Impacts on ecosystems will also affect the Arctic's indigenous populations, e.g. by increased risks to infrastructure and water resource planning (Bring et al., 2016), health (Geer et al., 2008) as well as subsistence based livelihoods (Ford et al., 2014). As an example of the latter, increased occurrences of rain events during the cold season, causing the formation of ground ice preventing winter grazing, will have negative impacts on herbivores, such as reindeer (Stien et al., 2012).

2.2.2. Remote impacts

In general, snow cover in the Pan-Arctic region has decreased over the last several decades (Screen and Simmonds, 2012; Shi et al., 2013), although for snow on sea ice our knowledge are limited due to effects of regional variability and a lack of direct observations. This has been attributed to elevated temperatures and increasing rain fraction of precipitation (relative to snow), but also the effects of increasing evaporation from the ocean due to receding sea ice pack should no be ruled out (Bintanja and Selten, 2014). In addition to local effects described above, changes in snow cover, especially during autumn-winter, influences the atmospheric circulation, which can yield remote impacts on hydroclimate on lower latitudes. For example, Cohen et al. (2012) suggested that a warmer and wetter Arctic atmosphere during autumn, caused by decreasing sea-ice coverage, regionally favours increasing snow cover in the same season, which dynamically forces negative Arctic Oscillation (AO) conditions in the subsequent winter. The negative phase of the AO is associated with a more meridoional flow of the jet stream, which allows cold Arctic air to penetrate into lower latitudes, occasionally yielding extreme weather events (Overland et al., 2016).

A distinct decline in sea ice extent and thickness has been observed in the past decades (Stroeve et al., 2012; Kwok and Cunningham, 2015). The melting of Arctic sea ice has local influences, but recent research suggest that it may also have remote impacts on the midlatitudes by perturbing local energy fluxes at the surface and modifying the atmospheric and oceanic circulation (e.g. Budikova, 2009; Francis et al., 2009). It has been suggested that variations in Arctic sea ice extent influences the North Atlantic Oscillation (NAO) (Pedersen et al., 2016), which has a strong influence on precipitation in the North Atlantic region (Hurrell, 1995; Folland et al., 2009). Wu et al. (2013) suggested that winter Arctic sea ice concentration may be a precursor for summer rainfall anomalies over northern Eurasia and Gou et al. (2014) noted a link between spring Arctic sea ice conditions and the summer monsoon circulation over East Asia. On the other hand, it is also likely that lower latitude phenomena influence Arctic sea ice conditions. For example, wintertime sea-ice loss has been linked to different phases of the Pacific Decadal Oscillation (PDO) (Screen and Francis, 2016).

Enhanced precipitation and melting of the cryosphere increases the runoff from the pan-Arctic land areas and lowers the salinity in the Arctic Ocean, and this will likely have significant impacts at a local, and potentially global, scale (Serreze and Barry, 2011; Rhein et al., 2013; Carmack et al., 2016). Since the density of the water in the Arctic Ocean determines the location of the thermo- and haloclines, changes in salinity may influence distribution patterns of organisms and biogeochemical properties (Aagard and Carmack, 1989; Carmack et al., 2016). Moreover, salinity regulates the density of the water in the Arctic Ocean, and through outflow of Arctic water into the North Atlantic it may impact regions at lower latitides, e.g. by affecting deep water formation in the Greenland-Norwegian and Labrador Seas and thus the strength of the THC (Aagard and Carmack, 1989; Rahmstorf, 1995; Salter et al., 2007). A disruption of the THC may have global impacts

(Vellinga et al., 2002). Density also determines the location of the thermo- and haloclines so that salinity shifts greatly influence distribution of organisms (Aagard and Carmack, 1989; Carmack et al., 2016).

3. Hydroclimate archives and proxies in the Arctic

While most archives and proxies that are widely used elsewhere to infer past climate variability can be found in the Arctic, their application require specific treatment and interpretation. The following section describes and discusses the characteristics and the limitations of these in the Arctic environment.

3.1. Lake sediments: varves and biomarkers

3.1.1 Arctic lakes

Most lakes in the Arctic appeared just after local retreats of glaciers and ice caps at the end of the last glaciation. Hence, their ages, and the potential lengths of the records they contain, are diverse across the Arctic, ranging from the entire Holocene in Beringia and Scandinavia, to a few hundred years in Greenland or Iceland. The last 2000 years were in general characterized by small glaciers advances, but with regional differences, prior to the general melt of the recent decades (Solomina et al., 2016). This relative stability in surface area over the last two millenia makes lakes excellent recorders of hydroclimate variability for this period. What makes the lakes different in the Arctic is the very strong seasonality that is reflected in a long, to very long, ice cover period. Ice cover substantially reduces the flux of particles to the bottom of the lake to amounts that are frequently not measurable, with the exception of some organic components. Therefore, what is recorded in Arctic lacustrine sediments is strongly biased towards the ice-free periods, i.e. spring snowmelt, short summer, and early autumn. Another charateristic of the Arctic is physical weathering related to gelifraction and sparse vegetation cover, making large quantities of easily-eroded minerogenic matter available to be transported into lakes (Zolitschka et al., 2015).

Lake systems in the Arctic differ depending on the presence or absence of glaciers in their watershed. Snowfed watersheds experience maximum discharge during snow melt in spring. They become depleted in water once the snow cover has melted away, reducing sediment transport in the later part of the ice-free season. On the other hand, glaciarised watersheds are not water-limited, i.e. the water supply to the lake tributary can last the entire summer and autumn until temperatures drop below zero. Discharge, and therefore sediment transport, is usually driven by temperature at the elevation of the glacier and is usually at a maximum during summer. In addition, lake systems in glaciarised watersheds may on rare occasions be subjected to catastrophic floods (called Jökulhlaups) which are due to collapsing ice dams retaining vast amounts of water in intra- or supra-glacial lakes, resulting in high sediment fluxes to the lakes.

Many watersheds in the Artic are also affected by the presence of permafrost. During summer, the permafrost thaws in its upper part (active layer), leaving sediment easily mobilised by small amounts of rainfall. This increases the risk of slope detachments, and can result in debris flows or very high sediment yields in lake tributaries (Lewis et al., 2005). The presence of permafrost also makes the dating of lacustrine sediments difficult because organic matter can be stored in the soils for a long period prior to being transported to the lakes (Abbott and Stafford, 1996).

In the High Arctic, sources of organic matter in lake sediments are both allochthonous and autochthonous, i.e. produced in the watershed or the lake. The relative contribution of these sources may, in part, be controlled by climate (Outridge et al., 2017), although the allochtonous organic mattter remains dominant, and the total amount preserved remains low (Abbott and Stafford, 1996; Galman et al., 2008). Conversely, lakes located in the southernmost part of the Arctic, such as in the Boreal Forest of Scandinavia or North America, experience a season with higher primary productivity. Their total organic carbon content can be relatively high (Galman et al., 2008) when anoxic conditions at the bottom of the water column prevail, slowing down its degradation.

3.1.2 Extracting hydroclimatic information from Arctic lakes

Most of the proxies used elsewhere in the world in the purpose of reconstructing past hydroclimate can be also analysed in Arctic lakes. Extensive experience has enabled their use in the Arctic in spite of the nature of the environment.

Pollen can successfully be used to reconstruct precipitation because the response of plants to moisture changes is direct and well-studied. Although a substantial proportion of the pollen in the High Arctic arrives from forested regions to the south, pollen assemblages can still be used to reconstruct the local conditions (e.g. Gajewski, 2002; 2006; 2015b). The sediments may be contaminated by older pollen stored in the soils or, in some cases, from Tertiary deposits in the watershed (Gajewski et al., 1995). Nevertheless, annual precipitation has been reconstructed, along with temperature (Gajewski, 2015a) using pollen assemblages, and are presented in section 4.2.

Chironomids: one of the primary factors affecting chironomids in the Arctic is lake depth, as is temperature and water chemistry (Gajewski et al., 2005). To the extent that changes in precipitation regime affect the depth of a lake, and the pH and nutrient supply, these can be used (Medeiros et al., 2015). However, most work has emphasized the reconstruction of temperature, and probably there would need to be very large changes in depth to have a noticeable effect on the chironomid community (e.g., Barley et al., 2006; Fortin et al., 2015).

Diatoms: Diatoms can presumably be used to reconstruct past moisture through various indirect methods. The primary control on diatoms is pH (Finkelstein et al., 2014), and to the extent this is affected by lake level variations, it could be used as an indirect proxy. Lake level changes affecting the relative area of deep and shallow water can be registered by diatoms;

these have been used in the south but not in the Arctic. A study of stable oxygen isotopes in diatom frustules allowed for a palaeohydrological reconstruction from Baffin Island, Canada (Chapligin et al., 2016).

Hydrogen isotopes and biomarkers: the source of environmental water in terrestrial systems is precipitation. Precipitation δD values are influenced by the location, temperature, and relative humidity of the primary evaporation source of the moisture, the air mass trajectory, and the temperature at condensation (Dansgaard, 1964; Boyle, 1997; Pierrehumbert, 1999; Masson-Delmotte et al., 2008; Frankenberg et al., 2009; Theaakstone, 2011; Sjolte et al., 2014). Evaporative enrichment can cause environmental water, including lake water, soil moisture, and leaf water, to become D-enriched relative to the original precipitation. Thus, lake sediment-based lipid δD records can provide important insights into variability of both precipitation δD values and evaporative enrichment, and ultimately to local hydrological changes. To date, there are only a handful of published studies using δD values of leaf waxes and algal lipids to reconstruct past hydrological changes in the Arctic (Thomas et al., 2012, 2016; Balascio et al., 2013, 2017; Moosen et al., 2015; Keisling et al., 2017). The palaeohydrological interpretations based upon these δD records differ among the studies, reflecting the fact that different lake catchments respond differently to hydrologic changes (and over different time scales), but also highlights our incomplete understanding of the biological and environmental factors that influence hydrogen isotope variability in lipids. Palaeohydrologic interpretations are better constrained when lipids with δD values representing lake water (e.g., those derived from algae and macrophytes) are considered together with those representing leaf water (e.g., long-chain *n*-alkanes and long-chain *n*-alkanoic acids) (Balascio et al., 2013, 2017; Rach et al., 2014; Muschitiello et al., 2015; Thomas et al., 2016). Together, δD values of these compounds can be used to quantify isotopic differences between lake water and leaf water, which can reveal changes in the duration of summer ice cover (Balascio et al., 2013), seasonality of precipitation (Thomas et al., 2016), or the vegetation type contributing lipids to the lake sediments (Balascio et al., 2017). Rach et al. (2017) propose an approach using paired terrestrial and aquatic lipid δD values and plant physiological models to quantitatively reconstruct relative humidity changes through time. This approach may prove effective in some Arctic settings.

Several physical and geochemical proxies have been used to infer past hydrology: *Mass accumulation rate* (MAR) is a measure of the amount of sediment accumulated at the bottom of the lake (e.g., Weltje, 2013). It is usually directly linked to the lake tributary discharge in lakes with low primary productivity (Petterson et al., 1999). Obtaining MAR requires an accurate age model and measurements of density. *Density*, *magnetic susceptibility* and *elemental composition* are all indicators of the detrital input, which is again linked to the lake tributary discharge (Petterson et al., 1999; Dearing et al., 2001, Cuven et al., 2010). *Grain-size* of the terrigenous fraction is an indicator of the competence of the flow (maximum discharge), its duration, and physical processes occuring in the lake water column (Lapointe et al., 2012). Altogether, these physical and geochemical proxies are rarely used in Arctic sedimentary sequences with massive structure because of the complexity of their interpretation, however, they proved to be powerful tools in annually laminated sediments.

3.1.3 Varved sediments

Varved sediments are difficult to find and probably rarely deposited (Zolitschka et al., 2015). However, several lakes with varved sediments have been found in the Arctic, most probably because the very strong seasonal contrast in sediment supply favors the formation of varves. Lakes containing varves tend to be deep enough to prevent bioturbation and are usually found in watersheds with high sediment yield. As such, many of the varved records cannot be directly compared to lakes used in diatom and pollen studies because the latter are usually studied in smaller systems. The advantages of varved sediments are that they contain their own internal chronology, that annual fluxes can be measured through the measurement of density, and that their properties can be calibrated against instrumental records (Hardy et al., 1996). In the Arctic, two types of varves exists: clastic varves and mixed clastic-biogenic varves, discussed in Zolitshcka et al. (2015).

3.1.3.1. Clastic varves

Clastic varves result from the complex interactions between sediment availability (geomorphological control), seasonal run-off variations carrying suspended sediment (hydroclimatic control), the thermal density structure of the lake water column and the bathymetry of the lake (limnological control). These varves are typically composed of a coarse-grained lower lamina that grades into a fine-grained upper lamina (e.g., Lake DV09; Courtney-Mustaphi and Gajewski, 2013; Lake C2; Zolitschka, 1996). Additional coarse grained laminae can be deposited and can be related to multiple pulses of snow melt or rain events (Ringberg and Erlstöm, 1999; Cockburn and Lamoureux, 2008). The finest clay fraction remains in the water column and is only deposited under quiet conditions during the following winter (Francus et al. 2008). Therefore, the presence of a distinct clay cap is the main criteria for identifying a year of sedimentation (Zolitschka et al., 2015).

Several individual parameters can be measured from each varve sequence: total thickness, sublamina thickness, density, mass accumulation rate, total and sublamina grain-size, elemental composition, and magnetic susceptibility. Linking these properties with hydroclimate conditions requires a minimal understanding (i.e. monitoring) of the processes occuring in the watershed and the lake, each system being different. Disentlangling the respective effect of the temperature from moisture is a challenge because due in part to the difficulty in obtaining data for calibration in the Arctic. When comparing varves' properties to observational climate data, they often contain signals of both temperature and precipitation (e.g. Table 2 of Cuven et al., 2011; Lamoureux and Gilbert, 2004), although the temperature signal has been more often reported in the literature. However, this may be because more robust measurements of instrumental temperature are available compared to precipitation (especially snow) and that, precipitation patterns tends to be more variable over a region, making correlation with sediment properties more difficult.

Despite these difficulties, several authors reported correlations of varve sequence data with hydroclimate. In general, the hydroclimate is revealed in the measurement of a specific part of the sedimentary cycle, and not by a parameter that integrates the whole year of sedimentation such as the total varve thickness. For instance, Lapointe et al. (2012) showed a correlation (r = 0.85, p = 0.0001) between the largest rainfall events and the coarsest grain-size fraction of each varves. Lamoureux et al. (2006) found a correlation between varve thickness of Sanagak Lake, Boothia Peninsula and snow-water equivalent in the watershed but they were unable to calibrate the series due to lack of calibration data. Francus et al. (2002) found a correlation (r = 0.53, p < 0.05) between snowmelt intensity and the median grain-size. Lamoureux (2000) found an association of sediment yield estimates of Nicolay Lake, Cornwallis Island, and rainfall events.

3.1.3.2 Mixed (clastic-biogenic) varves

In less harsh environments, such as in central Scandinavia, the vegetation in the catchment area and soils are more developed, allowing for decaying organic matter to be incorporated into the lacustrine system. At the same time, the primary productivity in the water column during the warmer seasons is large enough to be recorded in the sedimentary archive. This results in the accumulation of a mixed varve type, known as clastic-biogenic (or clastic-organic) varves. These typically contains a characteristic minerogenic lamina, usually showing graded bedding and that is directly related to the duration and strength of the spring flood (e.g. Ojala et al., 2000; Snowball et al., 2002, Tiljander et al., 2003), and a biogenic lamina that can be composed of autochthonous organic matter (e.g. diatoms frustules) and/or allochtonous organic debris.

Proxies measured with annual resolution on these mixed varves include 1) total varve thickness, 2) growing season lamina (GSL) thickness, 3) winter lamina (WL) thickness (Saarni et al. 2015), and 4) relative X-Ray densitometry (Ojala and Francus, 2002). Correlations with climate parameters vary from site to site and sometimes throught time in a single site (Saarni et al., 2015). Only a small number of lacustrine sequences, all of them from Scandinavia, have been sucessfully correlated to precipitation or moisture. At Lake Nautajärvi annual and winter precipitation was reconstructed using relative X-Ray densitometry (Ojala and Alenius, 2005), whereas at lake Kallio-Kourujärvi, the growing season lamina was linked to annual precipitation (Saarni et al., 2015). Rydberg and Martinez-Cortizas (2015) showed that high accumulation of snow resulted in high mineral matter content, and Wohfarth et al. (1998) found a significant correlation between early spring/summer precipitation and total varve thickness in north-central Sweden.

As with clastic varves, it is quite difficult to separate the temperature from the moisture signal. Ojala and Alenius (2005) showed that the direct annual and seasonal comparisons between raw varve data and instrumental measurements are complicated. Itkonen and Salonen (1994) showed that total varve thickness of three Finnish lakes were corrrelated with both temperature and precipitation, the correlation being weaker for precipitation. Nevertheless, sediment trap studies clearly but qualitatively showed the sensitivity of such systems to varying hydroclimate conditions (Ojala et al. 2013; Rydberg and Martinez-Cortizas 2015).

3.2 Peat deposits

3.2.1. Peatland processes and peat archive

Peatlands are wetland ecosystems that preserve their developmental history over millennia. Peat deposits are products of the balance between plant production and organic-matter decomposition (Clymo, 1984) and both processes are affected by climate. As a result, peat accumulation and processes are inherently influenced by autogenic/ecological and allogenic/climatic factors, as well as their interactions (Belyea and Baird, 2006). Many peat-based proxies (see below) have been used to reconstruct peatland hydrology and water-table dynamics, likely connected with regional hydroclimate. This inherent, dynamic change ability of wetland communities results largely from their occurrence in environments where a single extremely variable habitat factor, i.e. water supply, is predominant (Tallis, 1983). However, empirical and modelling studies show the importance of autogenic process and ecohydrological feedbacks (e.g., Tuittila et al. 2007; Swindles et al., 2012; Loisel and Yu, 2013; Väliranta et al. 2016). Clearly, consideration of biological processes and ecological feedbacks is needed when using these systems for climate reconstructions.

Peatland plants shape their own habitat since they form their own growth substrate: peat. Hence, peatlands are capable of recording in their deposits the effects of past vegetational and ecological changes. Within the peat lies a repository of botanical, zoological, environmental and biogeochemical information, which is important for understanding past climatic conditions. These palaeo records are used to estimate the rates of peat formation or degradation, past vegetation, climatic conditions and depositional environments (Moore and Shearer, 1997; Blackford, 2000). Analysis of peat deposits has undergone major developments during the last several decades regarding coring techniques, peat sampling and analysis, geochronology, identification of plant remains and other microfossils, and quantitative multivariate techniques (e.g. Barber et al., 1994; 1998; Väliranta et al. 2007; Charman et al., 2009; Chambers et al., 2011; Mathijssen et al. 2016; 2017).

Stratigraphic studies in peatlands have shown a hydroseral succession, where wet swamp and fen communities gradually develop into dry bog communities (Tallis, 1983; Korhola, 1992; Väliranta et al. 2016). These changes are largely autogenic, connected to growth of wetland communities, and caused by climatic variability or artificial drainage. Hilbert et al. (2000) developed a model of peatland growth that explicitly incorporates hydrology and feedbacks between moisture storage and peatland production and decomposition. They suggest that drier ombrotrophic peatlands (most bogs) will adjust relatively quickly to perturbations in moisture storage, while wetter ombrotrophic peatlands (mineral rich fens) are relatively unstable and can withstand only very small changes in water tables (Mathijssen et al. 2014). Climate change will affect the hydrology of individual peatland ecosystems mainly through changes in precipitation and temperature. As the hydrology of the surface layer of a bog is dependent on atmospheric inputs (Ingram, 1983), changes in the ratio of precipitation to evapotranspiration may be expected to be the main factor in driving ecosystem change. In particular, ombrotrophic peatlands are regarded as directly coupled to the atmosphere through precipitation and hydrology change (Barber et al., 1994), such that their water levels and dominant plants will reflect the prevailing climate. More specifically, their water-table variability has been shown to be highly correlated with the total summer seasonal moisture deficit (that is, precipitation – evapotranspiration; Charman, 2007).

Modern investigations of past climate are performed with an emphasis on obtaining the highest possible time resolution for a given archive. Radiocarbon dating is one of the main methods used to establish peat chronologies. The best material for ensuring accurate dates are aboveground remains of plants that assimilated atmospheric CO_2, e.g. short-lived plant macrofossils and pollen, whose ^{14}C age is consequently not affected by a old carbon effect. Suitable materials for sample selection are *Sphagnum* mosses (branches, stems and leaves) or, if not present, aboveground leaves and stems of dwarf shrubs (e.g. Nilsson et al., 2001; see however Väliranta et al. (2014)). Age-depth models that are considered ecologically plausible and that take into account likely modes of peat accumulation, include: (1) linear accumulation; (2) concave curves (through continuing decomposition of fossil matter in the peat deposit; Yu et al., 2001); (3) convex curves (with deposits slowing down their accumulation when close to a height limit; Belyea and Baird, 2006); and (4) Bayesian models that can include prior information on stratigraphy, accumulation rate and variability, and/or detect outlying dates (reviewed by Parnell et al., 2011). The robustness of age models can be significantly improved, and the uncertainties reduced, by using multiple dating methods on a single core. Most commonly, the uppermost layer can be dated using atmospheric fall-out radionuclides (e.g. ^{210}Pb; see Le Roux and Marshall, 2011) and spheroidal carbonaceous particles (SCPs) profiles (Yang et al., 2001), while tephrostratigraphy can potentially be applied throughout the core (Swindles et al., 2010). With suitable statistical treatment, all results can be combined into one reliable chronology which provides the backbone for interpretations of palaeoclimatic and palaeoenvironmental change data.

3.2.2. Peat-based hydroclimate proxies

Peatland formation can initiate via three processes: primary peatland formation, terrestrialization or paludification (Rydin and Jeglum, 2006). In primary peatland formation, peat is formed directly on wet mineral soil when the land is newly exposed due to crustal uplift or deglaciation, whereas in terrestrialization and paludification the area colonized by peatland vegetation has experienced previous sediment deposition or soil development (e.g. Tuittila et al., 2013). Information on hydroclimatic conditions can be derived from these processes, especially when the different peat formation types show systematic and isochronic patterns over wide geographic areas. For example, in paludification, the prerequisite is that the local hydrological conditions become wetter, for instance, induced by climatic change, fire or beaver damming, resulting in waterlogged soil conditions that promote peat accumulation (Charman, 2002; Gorham et al., 2007; Rydin and Jeglum, 2006). A new conceptual model of episodic, drought-triggered terrestrialization presents the infilling as an allogenic process driven by decadal-to-multi-decadal hydroclimatic variability (Ireland et al., 2012).

Recently, Ruppel et al. (2013) presented a comprehensive account of postglacial peatland formation histories in North America and northern Europe using a data set of 1400 basal peat ages accompanied by below-peat sediment-type interpretations. Their data, mainly focusing on Boreal-Arctic regions, indicates that that the peat formation processes exhibited some clear spatiotemporal patterns. Unfortunately, the overwhelming majority of the basal peat accounts originate from the deepest, and often the oldest parts of peatlands, and therefore the last two millennia are clearly underrepresented in the present data. However, existing studies illustrates the potential of using peat initiation and expansion data to account for changes in regional moisture regimes, also in more recent times. The formation of new peatland areas does not necessarily decrease when the initiation rates decrease but that new peatland areas are continuously formed via lateral expansion.

Peat bulk density (or organic matter density) in down-core profiles have been used to reflect overall peat decomposition, which in many peatland regions is controlled by surface moisture and hydroclimate conditions (e.g. Yu et al., 2003). The rationale is that well-preserved peat is loose and has low organic matter density, most likely deposited under wet conditions promoting protection of organic matter in an anaerobic environment. Peat bulk density values are typically 0.05 to 0.2 g cm^{-3} in high-latitude regions (Chamber et al., 2011). Peat humification is another proxy for the degree of peat decomposition. which can be estimated or measured in the field or laboratory using a range of methods (Chamber et al., 2011). Humification can be used as a proxy of peatland surface wetness – as moisture is a key determinant of decomposition – and regional hydroclimate in the Arctic (e.g. Borgmark, 2005; Borgmark and Wastegård, 2008; Vorren et al., 2012).

Net carbon accumulation is the balance between production and decomposition, both which are influenced directly or indirectly by climate (Yu et al., 2009). However, recent syntheses indicate that temperature-driven production might be more important than moisture-controlled decomposition in determining net peat peat accumulation (e.g. Beilman et al., 2009; Charman et al., 2013). Therefore, without constraints from other proxies, it is difficult to infer hydroclimate from peat accumulation records as also demonstrated in Mathijssen et al. (2016, 2017). As mosses are the dominant plants in peatlands, carbon isotopes from these mosses and peat are useful for inferring peatland moisture conditions. In wet conditions, water films around moss leaves will reduce conductance of pores on the leaf surface to CO_2 uptake, reducing discrimination against ^{13}C and resulting in high carbon isotope values (Rice, 2000). Carbon isotopes have been shown to reflect surface moisture in peatlands (e.g. Loisel et al., 2009). In addition, Nichols et al. (2009) used compound-specific carbon and hydrogen isotopes from peatlands in the Arctic to evaluate summer surface wetness and precipitation seasonality.

Because plant macrofossils reflect changing abundances of climatically sensitive peatland vegetation, they have been used not only for reconstructing the local vegetation history of peatlands but also for inferring past peatland hydrological changes and, by extension, regional climate variability (e.g. Barber et al., 1998; Hughes et al., 2000; Swindles et al., 2007; Väliranta et al. 2007; Mauquoy et al., 2008; Mathijssen et al. 2014, 2016, 2017). Traditionally, plant-based peatland surface wetness reconstructions have been qualitative or semi-quantitative, based on the identification of phases of relatively low local water tables (showing increased representation of hummock species) and phases of higher local water-table depths (lawn and hollow species) (Mauquoy et al., 2002; Pancost et al., 2003; Sillasoo et al., 2007). More recently, ordination techniques (e.g. PCA and DCA) have been used to create a single index of peatland surface wetness based on the total sub-fossil dataset for a peat profile (Barber et al., 1994; Mauquoy et al., 2004; Sillasoo et al., 2007; Zhang et al. 2017), in which it is assumed that the principal axis of variability in the dataset is linked to hydrology. The most recent progress in identification and quantification techniques of plant macrofossils (e.g. the Quadrat Leaf Count method, Mauquoy et al., 2010), together with careful calibration with modern plant community data, allows for the quantification of past peatland water table fluctuations with great accuracy. Väliranta et al. (2007) developed a transfer function by calibrating plant macrofossil records against the modern vegetation/water-table relationship, in order to quantitatively reconstruct peatland surface wetness trends for the late Holocene. The inferred water tables showed strong fluctuations, with an overall amplitude of ca. 40 cm. During the last two millennia, they found generally dry conditions until ca 1600 cal BP (ca.400 CE), varying water tables during the following four centuries, and dry conditions from ca 1200 to 700 cal BP (ca. 800-1300 CE, covering the MCA). The subsequent centuries were again variable, while the period 500-200 cal BP (1500-1800 CE, covering the LIA) was wet and the last two centuries dry except for the very recent years. The comparison of water-table reconstructions based on macrofossils and testate amoebae at two bogs in Estonia and Finland increased the confidence in using bog plants in quantitative hydrological reconstructions (Väliranta et al., 2011).

Testate amoebae (Protozoa: Rhizopoda) are unicellular animals with distinct environmental preferences, which live in abundance on the surface of most peat bogs. These amoeboid protozoans produce morphologically distinct shells, which are commonly used as surface moisture proxies in peat-based palaeoclimate studies (Mitchell et al., 2008). Although the moisture sensitivity of these organisms has been known for a long time, work over the past several decades has demonstrated the utility of testate amoebae as quantitative peatland surface-moisture indicators. Their indicator value in documenting surface-moisture variation has been demonstrated by coherence in reconstructions of wet and dry fluctuations within and between peatland sites (Hendon et al., 2001; Booth et al., 2006). A protocol of their use in paleohydrological studies is provided by Charman et al. (2000) and by Booth et al. (2010). Testate amoebae have been used for tracing hydrological changes in temperate peatlands in several regions of the world, as well as in boreal and subarctic peatlands of Canada and the US (Payne et al., 2006; Loisel and Garneau, 2010; van Bellen et al., 2011; Bunbury et al., 2012; Lamarre et al., 2012; Lamarre et al., 2013). In addition to bogs, their applicability also applies to fens (Payne, 2011). Recently, Swindles et al. (2015) and Zhang et al. 2017 tested the potential of testate amoebae for peatland palaeohydrological reconstruction in permafrost peatlands, based on sites in Arctic Sweden and Russia, respectively. These evaluations confirmed that water-table depth and moisture content are the dominant controls on the distribution of testate amoebae in Arctic peatlands, corroborating the results from studies in mid-latitude regions. New testate amoeba-based water table transfer functions were created with good predictive powers and the transfer functions were applied to short cores from permafrost peatlands. All records revealed major shift in peatland hydrology, where the one in Swidles et al. 2015 coincided with the onset of the Little Ice Age (ca. 1400 CE). The new modern training sets will enable palaeohydrological reconstruction from permafrost peatlands in Northern Europe, thereby permitting greatly improved understanding of the long-term hydrological dynamics of these ecosystems as well as the general variability in hydroclimatic conditions.

3.3. Tree-ring data

Distinct, precisely dateable tree-rings are generally formed in areas with pronounced seasonality, which results in a single period of cambial activity (growth) and dormancy per calendar year. The width, density and isotopic compositions of a tree-ring are partly determined by local weather and climate, and the closer to the ecological limit of distribution a tree grows, the more sensitive to climate it will be. Due to the large spatial distribution of trees across extratropical regions, their capacity to live for many years and their potential for developing precise, annually resolved chronologies, tree-ring data have been widely used to infer late Holocene variations in a range of climate parameters on local to hemispheric scales.

3.3.1. Tree-ring width and density

Measurements of annual tree-ring widths (TRW) are perhaps the most important data source for quantitative estimates of high- to low-frequency climate variability during the past centuries to millennia. The advantage of TRW comes from its annual resolution and a comprehensible understanding of the climatic controls on the tree-ring growth dynamics (e.g. Vaganov et al., 2006). Tree-rings have the advantage of numerical calibration, verification and potential to capture seasonal extreme events not possible using lower-resolution, less temporally well-constrained archives. The tree-ring community has generated an expansive network of TRW chronologies, covering a wide range of species and ecosystems, across the globe, not least in the Boreal-Arctic ecotones. In general, trees growing close to their latitudinal or altitudinal limit of distribution will be sensitive to warm-season temperature, while trees growing in semi-arid to arid regions are limited by precipitation/moisture (St George, 2014; St George and Ault, 2014; Hellman et al., 2016). Consequently, most, but not all, high-latitude TRW chronologies exhibit strong positive associations with summer temperature and only weak correlations with summer or winter rainfall. Tree-ring data from the high northern latitudes have been used in several reconstructions of Northern Hemisphere temperature (e.g. D'Arrigo and Jacoby, 1993, Jones et al., 1998; Briffa et al., 2001; Esper et al. 2002; D'Arrigo et al., 2006; Schneider et al., 2015; Stoffel et al., 2016; Wilson et al., 2016), as well as reconstructions targeting Arctic temperatures (Overpeck et al., 1997; Kaufman et al., 2009; Shi et al., 2012; Hanhijärvi et al., 2013; McKay and Kaufman, 2014). The few chronologies in the cool boreal and Arctic regions developed from precipitation sensitive trees are mainly located in continental climate zones, such as western Canada, Alaska and eastern Fennoscandia (see figure 1 in St George and Ault (2014)). Many TRW records are negatively correlated with summer rainfall, and most of these are found in the colder high-latitude regions. Positive correlations with prior-summer precipitation are also common across the Arctic. This carry-over effect may be caused by increased photosynthetic reserve accumulation in years with sufficient moisture supplying resources that can be used for secondary tissue growth in subsequent years. A proportion of this association likely reflects the inverse relationship between summer temperature and precipitation observed in these regions.

Although TRW is the most commonly used tree-ring proxy, at high latitudes wood densitometric measurements, specifically maximum latewood density (MXD) and its surrogate Blue Intensity (BI), are commonly being viewed as superior temperature proxies compared to TRW. It would seem that the strong correlation between MXD/BI and temperature would prevent their use in hydroclimate reconstructions. However, recent studies (Cook et al., 2015; Seftigen et al., 2015a; 2015b) have indirectly used high-latitude temperature sensitive tree-ring data to reconstruct soil moisture availability, by considering the inverse relationship between available soil moisture and clear skies, higher temperatures, increased evaporation, and reduced rainfall. Thus, the negative correlation between the high-latitude tree-ring data and drought metrics, such as the self-calibrating Palmer Drought Severity Index (scPDSI, van der Schrier et al., 2006a, b) and the Standardised Precipitation-Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010), can be used to generate reconstructions that are comparable to those from arid and semi-arid regions where tree growth is strongly limited by rainfall. Many high-latitude MXD data that are mainly influenced by temperature also exhibit a negative, albeit weak, statistical association with summer precipitation (Briffa et al., 2002). This mixed response explains why such data have successfully been used in reconstructions of drought indices that integrate both temperature and precipitation.

3.3.2. Stable isotopes in tree-rings

The isotopic ratios of wood, lignin and tree-ring cellulose are influenced by a different and more limited range of environmental and physiological controls than TRW and MXD. For this reason, stable isotopes in tree-rings provide additional palaeoclimate information to support and enhance the information attainable from the physical proxies (McCarroll and Loader, 2004, Gessler et al., 2014). Similar to the physical proxies of TRW and MXD, the strength and relative expression of these climatic controls will vary geographically and to a degree with local edaphic conditions and tree species. In simple terms, carbon isotopic variability reflect changes in the balance between conductance of carbon dioxide (CO_2) from the atmosphere to the site of photosynthesis, and assimilation rate, which are influenced by moisture stress and photosynthetically active radiation (PAR), respectively. Temperature and nutrient availability may also contribute to this signal through an influence upon the rate of chemical reactions and production of photosynthetic enzymes (Farquhar et al., 1982, Scheidegger et al., 2000, Hari and Nöjd, 2009). Oxygen and hydrogen isotopes are more closely related to the isotopic composition of the water used by the tree during photosynthesis, which may reflect a combination of moisture sources, subsequently modified by evaporative enrichment of leaf water (vapour pressure deficit and relative humidity) and plant physiological processes (Barbour et al., 2001; Danis et al., 2006; Treydte et al., 2014; Roden et al., 2000).

Since the earliest isotopic dendroclimatology studies conducted in the Arctic (Sonninen and Jungner, 1995; McCarroll and Pawellek, 1998; Waterhouse et al., 2000), several isotope studies have made significant contributions to palaeohydrology (e.g. Waterhouse et al., 2000; Holzkämper et al., 2008; 2012; Sidorova et al., 2008; 2009; Porter et al., 2009). The combination of long-lived trees, robust dendrochronologies and excellent sample preservation both on land and in lakes have facilitated the development of several multi-centennial to millennial length isotopic records (Boettger et al., 2003; Kremenetsky et al., 2004; Sidorova et al., 2008; Young et al., 2010; Gagen et al., 2011; Porter et al., 2014; Loader et al., 2015). However, because moisture is rarely the dominant tree-growth limiting factor across much of the Arctic region, there is a limitation to the hydroclimate information that can be reconstructed using the isotopic approach. Using a multi-parameter approach, several studies (Loader et al., 2013; Young et al., 2010; 2012; Gagen et al., 2011) provided sunshine/cloud estimates and were able to demonstrate large-scale shifts in the dominance of Arctic and Maritime air masses over the Northern Fennoscandian region during the LIA and MCA. Such multi-parameter studies are potentially very powerful as they help to develop testable hypotheses relating to the future response of the Arctic atmosphere and provide a foundation for developing a circum-polar isotope network to track changes in atmospheric circulation and its relationship to climate throughout the Common Era.

Reconstructions based upon oxygen and hydrogen isotopes are yet to reveal the same clear and stable correlations against instrumental data observed for carbon, but are likely to relate most closely to local and regional hydroclimate through their close link with stable isotopes in precipitation (Roden et al., 2000). The relative contributions of the isotopic signal from snowmelt and growing season precipitation used to form the tree-rings is an area requiring investigation. Links between $\delta^{18}O$ and both moisture and temperature have been identified (Sidorova et al., 2009; Knorre et al., 2010). Further south Hilasvuori and Berninger (2010) linked oxygen (and carbon isotopes) most strongly to cloud cover, with precipitation, relative humidity and temperature exhibiting lesser correlations. Hydrogen isotopes did not correlate as strongly as oxygen or carbon, with the strongest statistically significant relationships being with precipitation. Seftigen et al. (2011) linked $\delta^{18}O$ to precipitation, but noted that this relationship was unstable through time, possibly due to changes in the atmospheric circulation. If the same close relationship observed between water isotope composition and tree-ring cellulose in mid-latitude regions (Danis et al., 2006; Labuhn et al., 2014; Treydte et al., 2014; Young et al., 2015) is confirmed in the Arctic, then exciting the potential for developing long records of the isotopic composition of precipitation suitable for large-scale mapping of isotope climate (Hemming et al., 2007; Saurer et al., 2012; Young et al., 2015). Reconstructing the stable isotopic composition of precipitation will likely provide a more useful, more direct link to the global hydrological cycle “isotope climate” (Birks and Edwards, 2009; Bowen, 2010), than a statistical calibration of water isotopes developed against a measured (indirect) meteorological variable which may vary in the degree of its control across space or over time.

3.3.3. Tree-ring based hydroclimate reconstructions

Tree-ring data have been used to locally estimate a variety of hydroclimate variables, such as precipitation, drought, streamflow, cloud cover and snowpack (e.g. Stahle and Cleaveland, 1988; Waterhouse et al., 2000; Pederson et al., 2001; Meko et al., 2001; Woodhouse, 2003; Gray et al., 2003; Young et al., 2010, Gagen et al., 2011). Moreover, networks of tree-ring chronologies have been used to make spatial (or field) hydroclimate reconstructions (Nicault et al., 2007; Cook et al., 1999; 2004; 2010; Fang et al., 2010; Touchan et al., 2011; Hua et al., 2013). However, these studies have almost exclusively utilized tree-ring data from lower latitudes outside the Arctic region.

Within the Arctic, trees are naturally constrained to exist below the latitudinal tree line, extending as far as *ca*. 73°N in parts of central Siberia, and as noted above, the majority of the tree-ring data in the region comes from temperature sensitive trees.

Still, with careful site selection, it is possible to find trees that are sensitive to moisture variability, and a few studies have inferred past precipitation variability using ring-width data. Indeed, a handful of reconstructions of local hydroclimate from the Arctic have been published. These have mainly focused on late spring/early summer precipitation. The longest record, and presently most widely used high-resolution hydroclimate proxy for high-latitude Fennoscandia, comes from south-eastern Finland, where Scots pine TRW was used to reconstruct annual May–June precipitation over the last millennium (Helama and Lindholm, 2003). Later an updated chronology from the same region was used to highlight the distinct and persistent "mega drought" from the early 9th century to the 13th century CE (Helama et al., 2009). The same parameter was also reconstructed from Scots pine for east-central Sweden back to 1560 CE by (Jönsson and Nilsson, 2009). In North America, Pisaric et al. (2009) reconstructed June precipitation of the Northwest Territories, Canada using a TRW network. The only reconstruction of hydroclimate outside the growing season was presented by Linderholm and Chen (2005), who developed a 400-year long winter (September-April) precipitation reconstruction with 5-year resolution, based on Scots pine TRW data from west-central Scandinavia.

Focusing on hydroclimate field reconstructions, one of the earliest works to use tree-rings to reconstruct past moisture variability in a high-latitude region was the *North American Drought Atlas* (NADA, Fig. 3a). The atlas was first released in 2004 (Cook et al., 2004), then covering continental U.S., but later updated (Cook et al., 2007) with an expanded tree-ring network to include parts of the Canadian Arctic. Although significant portions of the latter region are at present under-represented in NADA, the tree-ring coverage still provides valuable hydroclimate reconstructions for a number of regions there. The summer PDSI reconstruction data for the Arctic part of NADA extends back to the 1000 CE, indicating slightly drier conditions during most of the MCA, except for a wet period in the 12th century, and a highly variable LIA albeit with a tendency for progressively wetter summers before the early 19th century (Fig. 3c). Two efforts have used extensive tree-ring data networks to infer past drought/pluvial variability for Fennoscandia (Seftigen et al., 2015a, 2015b) and Europe (The *Old World Drought Atlas*, OWDA, Cook et al., 2015, Fig. 3a). These atlases, where tree-ring data was used to create gridded (field) reconstructions of the SPEI (Seftigen et al., 2015b) and the scPDSI (Cook et al., 2015), included regions north of 60°N. These millennium-long reconstructions allow for detailed investigations of the MCA and the LIA. The MCA in continental Europe and southern Scandinavia was significantly drier that either the LIA or the post-industrial period (1850-present, and the reconstruction suggests that the Arctic regions in Europe experienced a severe drought during this period (Fig. 3b), which is in agreement with the findings of Helama et al. (2009). Interestingly, the timing of the MCA drought seems to temporally coincide with multicentennial droughts previously reported for large areas of North America (Cook et al., 2007), specifically in California and Nevada. This suggests a common forcing across the North Atlantic, likely related to the North Atlantic Oscillation (NAO) and/or Atlantic Ocean sea surface temperatures. However, the restricted temporal coverage of the high-latitude part of NADA does not provide an opportunity to compare hydroclimatic variability across the Arctic region during the MCA. Large-amplitude hydroclimatic variability is not only restricted to the MCA, as periods of dryness are recorded in the first half of the 15th century CE and in the 1750s-1850s, and may not have been restricted to the Arctic (Cole and Marsh, 2006).

Another possible option to derive hydroclimate information from north of the treeline in the Arctic is the utilisation of annual growth rings from shrubs. For example, Zalatan and Gajewski (2006) presented a short *Salix alexensis* growth-ring series from northwestern Victoria Island in the Canadian Arctic. The widths of the shrub rings were found to be correlated with winter precipitation. Although the reported record was too short to be useful for palaeoclimate studies, it may be possible to obtain longer series by using larger specimens (some are tree-sized in this area, Edlund and Egginton, 1984) or cross-dating dead and buried wood.

4.3.4. Pine regeneration patterns as indicators of hydrological shifts

In the high northern latitudes, tree remains can be preserved for several millennia buried in lakes or peat, so called subfossil wood, and subfossils extracted from lakes have been used to reconstruct temperatures for large parts of the Holocene in Fennoscandia (see Linderholm et al., 2010 for a review). More or less well preserved trees can also be found in dark layers of well-humified peat, an indicator of dry conditions having allowed trees to grow and to colonise the area (Gunnarson, 2008).

In west-central Sweden, more than 1000 subfossil and peatland Scots pine (*Pinus sylvestris* L.) samples have been collected since the late 1990s. Most samples come from different lakes at varying altitudes, and the temporal distributions of the dated samples show wavelike patterns of regeneration with clearly distinguishable mortality and germination phases. Such generation pulses have been related to climatic conditions favourable for seed production and successful germination, i.e. warm and dry periods (Zachrisson et al., 1995). However, Gunnarson (2008) suggested that temporal variation of pine samples from both bog and lakes (Fig. 4) reflect fluctuations in peatland ground water tables and lake levels caused by regional changes in hydroclimate. It is likely that these variations were governed by changes in precipitation rather than changes in temperature. In southeastern Finland evidence of depositional histories of subfossil pines from lakes, where most trees have grown adjacent to or on lake shores (so called riparian trees), and peatland pines were combined by Helama et al. (2017a). Divergent depositional histories (i.e. replication curves) were obtained for the two environments during the Common Era. High accumulation of peatland pines during the MCA indicates dry surface conditions beneficial for pine colonization (Torbenson et al., 2015; Edvardsson et al., 2016). This phase overlapped with a phase of low accumulation of riparian pine trees. In contrast, the accumulation of riparian pines increased towards the LIA, culminating around 1300 CE, suggesting rising lake water level contributing to tree mortality and increased preservation potential of trees in lakes. Again, this phase overlapped with a phase of strongly declined accumulation of peatland pine trees. These results were supported by taphonomic interpretation (Gastaldo, 1988) of the depositional histories, especially their dissimilarities, and by comparisons with palaeolimnological reconstructions of water level fluctuations during the MCA and LIA (Luoto, 2009; Nevalainen et al., 2011; Nevalainen and Luoto, 2012). Similar to the study conducted in west-central Sweden (Gunnarson, 2008), the depositional histories in southeastern Finland were found to reflect past hydroclimatic variations. Likely, the replication in pine chronologies from near the northern edge of the species range reflects summer temperature conditions, especially in subarctic sites (Helama et al., 2005; 2010). Further south, tree accumulation in different sediments seems to be more strongly influenced by recruitment and preservation potentials which, in turn, are driven by local hydroclimatic conditions.

3.4. Glaciers

3.4.1. Glaciers as direct and indirect climate indicators

Glaciers respond to climate changes through variations in length, area and volume (Oerlemans, 1994, 2001). In the Arctic and subarctic, observations and indirect evidence of glacier fluctuations, have been widely used as sources of information about past climates (Solomina et al., 2016 and references therein). Changes in glacier length through advances or retreats are indirect, lagged responses to climate change, while glacier mass balance variations, as indicated by changes in ice thickness and volume, are direct responses to the annual weather conditions (Haeberli and Hoelzle, 1995). Direct measurements of glacier variability across the world, derived from annual mass balance measurements using glaciological or geodetic methods, are generally limited to the last half century (Zemp et al., 2009). In addition, annual mass balance records have been extended for several centuries using meteorological and proxy data such as historical records and tree-ring data (e.g. Lewis and Smith, 2004; Watson and Luckman, 2004; Nordli et al., 2005; Linderholm and Jansson, 2007). However, to yield information about glacier variability beyond the direct observation, indirect indicators are mainly used.

There are two types of indirect glacier records: classical discontinuous series usually based on moraines delimiting the former glacier positions and continuous records from e.g. lakes (Solomina et al., 2016). Geomorphological evidence of glacier advances, such as terminal moraines or proglacial lacustrine sediments, give relative dates of glacier fluctuations, usually with some uncertainty. Lichenometry, a method where lichen dimensions are used to infer the timing of colonisation, can provide rough estimates of moraine formation (Bickerton and Matthews, 1992; Armstrong, 2004). If the moraines contain organic material, they can be dated by ^{14}C (Karlén and Denton, 1976) or dendrochronological methods (Luckman, 1993; Carter et al., 1999). Cosmogenic isotopes (e.g. ^{10}Be) can be used to directly identify the age of moraine deposition (Gosse and Phillips, 2001; Granger et al, 2013). Continuous records derived from lake sediment properties represent both the advance and retreat phases of glacier variations (Dahl and Nesje, 1994; Matthews et al., 2005; Bakke et al., 2008). As soon as the meltwater signal in proglacial lake sediments co-varies with the distance between the glacier and the lake, it can serve as an indicator of glacier extent and the corresponding Equilibrium Line Altitude (ELA), which is the altitude where accumulation equals ablation (Dahl and Nesje, 1994). Reconstructions of the ELA are based on multi-proxy sediment analysis (e.g. loss-on ignition, bulk density, magnetic susceptibility grain-size distribution, and AMS dating control).

Glacier mass balance measurements demonstrate that for most regions summer temperature is the dominant control on annual mass balance (Koerner 2005; Björnsson et al., 2013). Some exceptions have been noted; glacier advances in coastal areas of Scandinavia, SE Alaska, Kamchatka and New Zealand in the late twentieth century were forced primarily by high winter precipitation (e.g. Lemke et al., 2007). This means that in order to derive precipitation information from records of glacier variations, the data should be complemented by independent temperature reconstructions. Thus, if the advance of a glacier corresponds to inferred warm summers (which would lead to increased ablation), it is likely that the advance was due to increased precipitation during winter (and vice versa). As has been noted previously, temperature proxies are readily available in the northern high latitudes. Various summer temperature proxies have been used to interpret past glacier fluctuations: macrofossils at the upper tree line (Dahl and Nesje, 1996), pollen (Bakke et al., 2008), chironomids (Axford et al., 2009), tree-ring data (Anchukaitis et al., 2013), sedimentary chlorophyll content (Boldt et al., 2015), melt features (Henderson, 2002), borehole temperatures (Wagner and Melles, 2002) and oxygen isotopes from ice cores (Kirkbride and Dugmore, 2006). Several sources of uncertainty should be taken into account when this approach is applied, such as the lag between glacier advances and corresponding climatic forcing, which may last for decades even for moderate size glaciers (Oerlemans, 2001) and the dating uncertainties for both geomorphic and stratigraphic data (for details see Nesje, 2009; Solomina et al., 2015; 2016).

3.4.2. Hydroclimate signals inferred from glacier fluctuations

Numerous detailed reconstructions of winter precipitation during the Holocene are available from Norway, where the mass balance of many maritime glaciers largely depends on accumulation rather than temperature changes (Nesje, 2009). Dahl and Nesje (1996) calculated winter precipitation at Hardangerjøkulen in southcentral Norway using proglacial sediments and tree line altitude variations over the Holocene. They found that winter precipitation during the period from 1250 cal. BP to 600 cal. BP (ca. 750 to 1400 CE) were similar to today's values (reference period 1961-1990). It then increased to more than 120% compared to the modern values until the LIA maximum (1750 CE) before being reduced again with up to 90%. These results conflict with those obtained from Bjørnbreen in central Norway, where a comparison of the ELA with reconstructed July temperature showed that the highest values of winter precipitation during the past two millennia occurred in the MCA at around 1000 CE (Matthews et al., 2005). The explanation for this disagreement could, to some extent, be related to the high spatial variability of winter precipitation in Norway. To explore the spatial precipitation patterns in Norway during the Holocene, Bakke et al. (2008) used data from two proglacial sites at Folgefonna (southern Norway) and Lenangsbreene (northern Norway) together with a pollen-based July temperature reconstruction. They found that the differences in the distribution of precipitation were related to the changes in the position of the westerlies. The southernmost position of the westerlies, leading to a smaller S-N precipitation distribution gradient and large positive precipitation anomalies during the last 2 ka in western Norway, occurred around 800 and 1600 CE. The suggested link between the atmospheric circulation (NAO) and precipitation/ glacier fluctuations (Nesje, 2009), is supported by the advance of Nigardsbreen in Southern

Norway between 1710 and 1735 CE, which was attributed mainly to increased winter precipitation linked with a period of the positive mode of the NAO (Nesje and Dahl, 2003).

Early studies of glacier advances during the LIA on Svalbard interpreted them to be responses to low temperatures (Svendsen and Mangerud, 1997; Humlum et al., 2005). However, some recent studies attribute a number of them, at least those that occurred in the 19th and early 20th centuries, to increased precipitation associated with a positive phase of the NAO (Reusche et al., 2014 D'Andrea et al., 2012). In western Svalbard, Røthe et al. (2015) suggested that open water associated with a loss of sea ice was the source of increased precipitation leading to the advance of Karlbreen glacier from *ca*. 1700 to 1500 cal. yr. BP (*ca*. 300 to 500 CE). The large LIA glacier advances in coastal areas on Iceland could also reflect increased precipitation (Kirkbride and Dugmore, 2006). Based on geomorphological evidence and ^{14}C dating, Lubinsky et al. (1999) identified glacier advances during the ~10th, and 12th centuries, 1400 and 1600 CE, and in the early 20th century in Franz Josef Land. The last advance occurred despite warm summers, as recorded from melt features in the Windy Dome ice core, due to anomalously high snow accumulation (Henderson, 2002). A glacier advance at *ca*. 1400 CE was also noted in Novaya Zemlia (Polyak et al., 2004). This was a time of increased winter precipitation as interpreted from the GISP2 ice-core record (Zeeberg and Forman, 2000). Wagner and Melles (2002) suggested that the Holocene fluctuations of the Ymer Ø ice cap in east Greenland depended mainly on precipitation since the inferred fluctuations disagreed with the Greenland borehole temperature. The advance of glaciers in the Miki and IC Jacobsen Fjords in eastern Greenland, which have been dated with lichenometry to around 900-950 CE corresponds to the MCA, and could also reflect the response of glaciers to increased precipitation (Geirsdóttir et al., 2000).

In Alaska, most glacier advances have been related to cool summers (Anchukaitis et al., 2013; Wiles et al., 2014). However, the MCA advance of the Sheridan Glacier (Zander et al., 2013), also observed for glaciers in Alaska and western Canada (Menounos et al., 2009; Koch and Clague, 2011), can be probably attributed to increased precipitation due to extended La Niña like conditions (Koch and Clague, 2011). The advance of the Sheridan Glacier in 1600s CE coincides with warming summers as recorded by tree-rings (Anchukaitis et al., 2013) and a peak in sedimentary chlorophyll (Boldt et al., 2015), and is thus probably also a sign of increased winter precipitation. Using lichenomety-dated moraines and the density of the sediment in Kurupa Lake (the Brooks Range in Alaska), Boldt (2013) produced continuous reconstruction of ELA variations for several glaciers in the region. By regressing ΔELA against average Arctic-wide summer temperatures from Kaufman et al. (2009), and using the residuals as a proxy for winter accumulation, he identified periods of increased (150-550, 650-1000 and 1500-1650 CE) and reduced (600, 1050-1450 and 1750 CE) accumulation. In the Chugach Mountains, south-central Alaska, McKay and Kaufman (2009) used the differences between inferred summer temperature and evidences for glacier advances and retreats to suggest a period of increased winter precipitation from 1300 to 1500 CE, and reduced winter precipitation from 1800 to 1900 CE, changes which were likely associated with variability in the strength of the Aleutian Low.

3.4.3. Hydroclimate from ice cores

Ice cores provide information of past climates through analysie of the annual layers deposited on glaciers. Several ice core parameters are used as palaeoclimate proxies, such as isotopic composition (mainly temperature), dust (e.g. storminess, aridity), air bubbles (atmospheric composition) and acidity (volcanic eruptions) (Rozanski et al., 1997). Ice core data have been used to infer past hydroclimate variability, mainly at lower latitudes like Tibet (e.g. Thompson et al., 2000; Yao et al., 2008) and the Andes in South America (e.g. Thompson et al., 1985). If annual layers can be identified and dated in ice cores, annual accumulation may be interpreted as records of past precipitation rates (Paterson and Waddington, 1984), however the accuracy of the reconstruction is affected by processes such as re-distribution by wind, melting and dating/measuring errors (e.g. Mosley-Thompson et al., 2001). The cosmogenic isotope ^{10}Be can provide estimates of palaeoaccumulation rates (Yiou, et al. 1997). Paterson and Waddington (1984) analysed ice core accumulation rates from Camp Century (Greenland) and Devon Island ice cap (Arctic Canada) and concluded that precipitation rates had only shown minor fluctuations during the last 2k, being similar to present conditions. Direct studies of ice core accumulation rates on Greenland have aimed at providing better understanding of spatiotemporal mass balance variability (e.g. Mosley-Thompson et al., 2001; Box et al., 2013), estimating precipitation trends (Mernild et al., 2015), or assessing links between precipitation/accumulation and large-scale modes such as the NAO (e.g. Appenzeller et al., 1998). Such long-term accumulation records may be useful for hydroclimate estimations. Box et al. (2013) provided a reconstruction of annual Greenland ice sheet snow accumulation showing an increasing trend in accumulation over the last 410 years. Ljungqvist et al. (2016) used "lamina thickness" from 5 sites across the Greenland ice sheet as proxies for annual precipitation in their hemispheric hydroclimate reconstruction (Supplementary Table 1 in their paper).

4. Regional comparisons

Here we present comparisons of hydroclimate records from two of the most densely sampled regions in the Arctic.

4.1. Canadian Arctic

In the Canadian Arctic Archipelago, available quantitative palaeoclimate reconstructions fall into three classes of data: (a) relatively low temporal resolution (100-year) regional precipitation reconstructions from pollen assemblages for the boreal zone, (b) individual site-based reconstructions of lake level or precipitation, sampled at variable but relatively low temporal resolution, based on various proxies, and (c) annually-resolved reconstructions typically based on varves or tree-rings. The most extensively used palaeoclimate proxies in this region are pollen records from lake sediment cores. Typically annual precipitation, along with temperature, or lake levels have been the targets for reconstructions (Gajewski, 2015). An extensive modern database of pollen data (Whitmore et al., 2005) enables quantitative reconstructions, and a number of reconstructions are available from the Canadian Arctic. A recent review of Holocene climate variations in the Canadian Arctic also indicated a number of other proxies in use (Briner et al., 2016), based on isotope or other physical or chemical measures. Presently, there are few published hydroclimate reconstructions using other proxies, although they have the potential to produce records with high temporal resolution. However, networks of these are not yet available. Most of the records are considered as temperature records, even if some have been related to moisture and sometimes to storms.

Viau et al. (2008) and Viau and Gajewski (2009) presented regional reconstructions of annual precipitation using all available pollen records from the boreal zone of Canada and Alaska (Figs. 5-6, table 1). At the scale of this study, spatial patterns in the precipitation reconstructions are not clear. In western Canada and Alaska, there was an increase in precipitation during the past 2000 years, whereas a long-term decrease was seen towards the east. There was no clear difference between the MCA and LIA (Fig. 5). From the Canadian Arctic, only four low-resolution reconstructions of annual precipitation are available and these are based on pollen records (Peros and Gajewski, 2008; 2009; Peros et al., 2010). They all show a comparable signal, with lower precipitation during the MCA and slightly higher moisture during the LIA, and during the period from 400 BCE to 600 CE, slightly earlier at site KR02 from Victoria Island (Fig. 6).

4.2. Fennoscandia

In Fennoscandia, palaeolimnological studies have recently produced records indicative of past regional hydroclimatic variability. Such records are based on micro-, macro- and megafossil assemblages in addition to lithological data. Here we use sixteen palaeolimnological records from the Arctic region (Table 2, Fig. 7) to illustrate hydroclimatic shifts and variations in Fennoscandia over the Common Era. The records are derived from depositional histories of subfossil trees (Gunnarson et al., 2003; Gunnarson, 2008; Helama et al., 2017a), estimates of peat humification (Gunnarson et al., 2003; Andersson and Schoning, 2010), sediment grain-size (Si/Ti; Berntsson et al., 2015), varve thickness (Saarni et al., 2015), varve minerogenic lamina (‘light sum’ sensu Saarni et al., 2016), plant macrofossils (Väliranta et al., 2007), and chironomids or cladoceran assemblages (Luoto, 2009; Luoto and Helama, 2010; Nevalainen et al., 2011, 2013; Nevalainen and Luoto, 2012; Luoto and Nevalainen, 2015; Berntsson et al., 2015). These records originate from Sweden and Finland and represent inland areas east of the Scandinavian Mountains.

Visual inspection of Fig. 7 does not indicate any strong agreement among the records. Overall, the proxy dataset suggest highly variable hydroclimatic conditions in Fennoscandia throughout the Common Era. The result also shows variations among the different proxies. Correlating the smoothed series (green lines in Fig. 7) yields correlations as low as 0.08. In fact, one might expect to find such disparity considering the peculiarities in local climate and range of proxy types, with an additional issue arising from dating uncertainties. However, dating issues may not constitute a critical factor for the observed low correlations among the records; comparing the depositional histories of subfossil trees from lake archives in Sweden (SWE01; Gunnarson et al., 2003; Gunnarson, 2008) and Finland (FIN12; Helama et al., 2017a), dated by means of dendrochronology and thus without dating uncertainties, results in a correlation of -0.20. The highest correlation between any pair of sites (0.83) is obtained between the two cladoceran-based lake water depth reconstructions from southern Finland

(FIN08 and FIN14; Nevalainen et al., 2011; 2013). The highest inter-proxy correlation of 0.72 was found between the cladoceran-based lake water depth reconstruction (FIN07; Nevalainen and Luoto, 2012) and FIN12, where both multi-proxy records come from southern Finland (Helama et al., 2017a). Among the Swedish data, the highest correlation of 0.42 was obtained between the peat humification index (SWE03; Gunnarson et al., 2003) and a chironomid-based record of catchment erosion (SWE05; Berntsson et al., 2015). The highest inter-country correlation of 0.54 was found between SWE05 and lake water depth (FIN14; Nevalainen et al., 2013).

The difference between the proxy value means over the two periods, the LIA and the MCA, was computed for the Fennoscandian records. Nine out of sixteen records indicate wetter conditions towards the LIA, and eight of these records are located in Finland. Four out of seven proxies that indicate drier LIA conditions originate from Sweden. Although these findings imply a more pronounced change towards wetter conditions in the eastern part of the region, it is also possible that part of these differences arise from varying sensitivity of the proxies to different seasons. While most of the studied proxy records likely represent hydroclimatic variations during summer, at least four of the records indicating relatively drier LIA (Luoto and Helama, 2010; Berntsson et al., 2015; Saarni et al., 2016) may actually reflect climatic and environmental factors attributable to boreal winter/spring phenomena, such as flooding, erosion, stream flow. In Boreal settings, a peak in runoff is generally attained during the spring season. The strength of this peak is strongly related to snowmelt and, in fact, the respective proxy data may be largely responding to antecedent snow conditions and thus winter precipitation. This has previously been described for eastern Finland, where a collection of proxy records reflecting either winter/spring or summer variability were found to exhibit contrasting hydroclimatic trends in respective variables through the MCA and LIA (Luoto and Helama, 2010). Therefore, the observed division of proxy records according to their indications of climate becoming either wetter or drier through the MCA-LIA transition, may reflect, at least partly, their response to precipitation in either winter/spring or summer.

The issue of seasonal responses may be particularly interesting in the context of the long-term development of the NAO. The Fennoscandian study sites are situated in a region where the positive NAO phase is attributable to increases in precipitation, and thus enhanced snowfall, during winter (Hurrell, 1995), but with decreased precipitation during much of the summer season (Folland et al., 2009). The different seasonal responses may, at least partly, explain the deviating patterns of hydroclimatic trends through the MCA and LIA among the proxies if the same climatic forcing (i.e. NAO) is anticipated to result in contrasting trends in respective records, according to their target season sensitivity. These results are in line with a possibly predominantly positive NAO phase during the MCA, associated with generally wet winters but dry summers (Trouet et al., 2009), while a negative NAO phase during the LIA has been linked with dry winters and wet summers (Luoto and Helama, 2010; Luoto et al., 2013; Luoto and Nevalainen, 2017). While the view of a prolonged positive phase during the MCA has been challenged by recent proxy observations (Ortega et al., 2015), additional support of a generally positive NAO phase overlapping the MCA have also been presented (Wassenburg et al., 2013; Baker et al., 2015). Still, it is notable that not all of the analysed proxies indicated any distinct change from the MCA to the LIA. Moreover, the records are characterised by low resolution, and high autocorrelation makes it difficult to perform any statistical tests for this change so the results should be regarded cautiously.

Compared to the hydroclimate fluctuations during the MCA and the LIA, a notable feature that characterises several of the Fennoscandian proxies (SWE03, SWE05, FIN07, FIN08 and FIN14) during the first millennium CE is a dry pre-MCA period of multi-centennial duration (Fig. 7). The timing of this phase appears to overlap with that of Dark Ages Cold Period (DACP, ca. 300-800 CE; Ljungqvist, 2010; Helama et al., 2017b; 2017c). Apart from climatic changes related to temperature fluctuations, the DACP was likely a period of marked variable climate conditions. A review of the palaeoclimate during the DACP showed that both wet and dry conditions have been noted in north-west Europe (Helama et al., 2017b). Using peat humification records Blackford and Chambers (1991) showed multi-site indications towards wet conditions for the British Isles around 550 CE. Likewise, indications of wet rather than dry spring/summer conditions during the DACP have been noted around North-West Europe (Helama et al., 2017b). Thus, despite an indication of dry conditions during the DACP in some of the Fennoscandian records, the findings would imply a general lack of agreement between the available proxy indicators to demonstrate any well-defined hydroclimate DACP anomaly.

Finally, there is no general tendency for any anomalous 20th century conditions among the records. While some of the series exhibit trends towards wetter conditions during the past century, other records indicate relatively drier conditions over the same period (Fig. 7). This finding implies that no unprecedented hydroclimatic changes, as recorded by the Fennoscandian dataset, can be linked to anthropogenic factors over the most recent past. However, the value of this finding is limited by the fact that the post-1950s interval is not present in more than half of the records, but it is in agreement with the findings of Seftigen et al. (2015b). These results are contrasted, however, by the new precipitation tree-ring based reconstruction just south of the region, from Estonia, where an upward trend in most recent summer precipitation was found unprecedented since the eighteenth century CE (Helama et al., 2017d).

5. Arctic hydroclimate synthesis from proxies and PMIP3 simulations

5.1. A composite of Arctic hydroclimate variability during the last 1200 years

As noted in the introduction, Ljungqvist et al. (2016) presented a reconstruction of northern hemisphere hydroclimate variability focusing on centennial variability, where the Arctic region was represented by 18 records. Here a new synthesis of Arctic hydroclimate variability extending back to 800 CE is performed, utilizing both high-and low-resolution records. Note that this is not a quantitative reconstruction, but only provides a qualitative view of relative hydroclimate variability in the

Arctic. The aim is to assess the potential to derive an Arctic hydroclimate record with more high-frequency information than that derived for the same region from the results of Ljungqvist et al. (2016).

The length of the analysis is restricted by the temporal coverage of the available series. In order to make a comparison with the PMIP3 simulations (see below), the analysis was focused on the last 1200 years. All records have been used in previous studies and are publicly available (Sundqvist et al., 2014, doi:10.5194/cp-10-1605-2014-supplement; Ljungqvist et al., 2016, www.ncdc.noaa.gov/palaeo/study/19725; Weißbach et al., 2016, doi:10.1594/PANGEA.849161). The dataset is composed of 40 series and is based on a heterogeneous group of proxy sources: 17 records are from ice cores, 16 from lake sediment, 6 from peat and one series is from tree-rings (Fig. 8, Table 3). The majority of the records are located in the North Atlantic area (Fennoscandia, Greenland and the Canadian Arctic) and Alaska.

Rather than just merging all existing records, the selection of the proxy records followed several quality criteria (McKay and Kaufman, 2014). Specifically, all records should i) be from north of 60°N; ii) extend back to at least 800 CE; iii) extend into the 1900s CE in order to include the recent warming period of the 20th century (PAGES 2k Consortium, 2013); iv) have an average sample resolution of less than 50 years; and v) have at least two age control points during the defined study period. Following these criteria, 17 records were selected (Fig. 8, Table 3). These strict selection criteria are necessary to allow for comparison of data at centennial scales and facilitate time series analysis. The spatial coverage is mainly confined to Alaska, Arctic Canada, Greenland and Fennoscandia, but these well-dated records, including many annually resolved records such as ice cores and varved sediments, offer the possibility to interpret hydroclimate variability in the Arctic from low to high frequencies.

To extract a common pattern from the records, we created an average signal in order to reduce random variability and enhance a possible Arctic hydroclimatic signal (Moron et al., 2006; Hassan and Anwar, 2010). Although such a common signal obtained from several climatic proxies can not be considered as a reconstruction, it is suitable for investigating and exctract different modes of variability present in the various hydrological signals. The resulting composite is not only reflecting precipitation, but most likely a combination of processes related to the hydrological cycle (precipitation, evaporation etc.). By calculating a standardized index of the palaeoclimatic series, we reduce the "external" variance (Zwiers, 1996 ; Rowell, 1998), i.e. the part of variance that is not spatially coherent. This external part of the signal can be considered as the part of the spatially independent stochastic (red or white) noise of a broad-scale climate signal.

Trend analysis was performed using the Mann-Kendall test (Mann, 1945; Kendall, 1975), a non-parametric test, which does not require the data to be normally distributed and it has low sensitivity to abrupt breaks in an inhomogeneous time series. The Mann-Kendall's tau statistic corresponds to the strength of the relationship between variables and gives values between -1 and +1. Positive values indicate that the ranks of both variables increase together, indicating an increasing trend, while a negative values indicate decreasing trend. The closer to +1 or -1 values of Kendall's tau, the stronger the trend in the time series. For this study, we choose the 95% confidence level. All records were standardized (i.e. zero mean and unit standard deviation) to be comparable with each other.

Continuous Wavelet Transform (CWT) allows the decomposition of a time series over a time-scale space. It is used for analysis of non-stationary processes that contain periodic or aperiodic components, noise and progressive or abrupt changes (progressive transitions, singularities and breaks) (Debret et al., 2007; Steinhilber et al., 2012; Lapointe et al., 2017). The resulting plot of the wavelet transform, also called a scalogram, is a frequency contour diagram with time on the x-axis, frequency, wavelet scale or equivalent Fourier period on the y-axis and power on the z-axis. The region of the spectrum for which the zero padding decreases the power of the wavelet transform is known as the cone of influence. In this area, energy bands are likely to be less powerful than they actually are. To determine the significance of the observed signal fluctuations, local wavelet spectra were compared to spectra of random signals that would theoretically correspond to other realizations of the same random process. We again choose the 95% confidence level (Torrence and Compo, 1998).

The results of the trend analysis show a significant negative trend between 800 and 1075 CE (tau = -0.404, p-value < 0.01), whereas during the last 900 years, no clear trend is evident (tau = 0.013, p-value =0.57) (Fig. 9). A distinct decrease between 1456 and 1485 CE is also noticeable. A wavelet analysis reveals variability on multidecadal to multicentennial scales (Fig. 10). Because wavelet analysis is sensitive to large events that may hide the lowest frequencies recorded, the 1456-1485 CE event was extracted by wavelet filtering and the signal reconstructed by inverse Fourier transform before using CWT. A ~80-year oscillation is present from 1050 to 1500 CE, while a ~ 140 year oscillation is present from *ca*. 900 to about 1650 CE.

To determine the influence of the spatial distribution on the variability recorded in our Arctic mean record, the Pan-Arctic record was compared with two regional records derived from data from the North Atlantic region (12 series) and Alaska (5 series) (Fig. 11). Visual comparison and correlation analysis between the Arctic mean record and each regional mean record indicate a stronger influence of the North Atlantic (r^2=0.93, p-value < 0.01) compared to Alaska (r^2=0.35, p-value < 0.01). This, however, should not be over-interpreted as 12 of the 17 records included in the Pan-Arctic record are from the North Atlantic. Increasing the spatial coverage of hydroclimate proxies in Eurasia and North America will allow a better understanding of overall hydroclimate variability in the Arctic.

5.2. Comparing Pan-Arctic hydroclimate from proxies with PMIP3 simulations

In addition to hydroclimate proxies, palaeoclimate modeling provides another mean to investigate temporal and spatial hydroclimate variability in the Arctic during the last millennium. As a part of the third phase of the Palaeoclimate Modeling Intercomparison Project (PMIP3: Braconnot et al., 2012), last-millennium climate simulations were performed using a set of atmosphere-ocean general circulation models according to the same experiment-protocol (Schmidt et al., 2012). These simulations cover the period of 850-1850 CE, and can be used to investigate climate responses to changes in external forcings, such as solar irradiance and volcanic eruptions. Some of the included models were also used to simulate climate variability for the period 1850-2005 and these are referred to 'historical simulations' (Taylor et al., 2012). In this section, 6 simulations (including 3 last-millennium simulations and 3 historical simulations) performed using 3 atmosphere-ocean general circulation models (AOGCMs, Table 4) including HadCM3 (Schurer et al., 2013), IPSL-CM5A-LR (Dufresne et al., 2013) and MPI-ESM-P (Jungclaus et al., 2014), were used. Modelled Arctic precipitation was then compared to the reconstructed Arctic hydroclimate by Ljungqvist et al. (2016, henceforth referred to as L16) as well as the new synthesis presented above. Both hydroclimate reconstructions and simulated annual total precipitation were transformed into z-score series, because the reconstructions represent hydroclimate indices that are not comparable with annual total precipitation. Because L16 has centennial resolution, data from the simulations and the new synthesis were filtered using Gaussian filter to preserve centennial-scale variability.

In the L16 reconstruction, it was wetter in northern than in southern Fennoscandia during the MCA compared to the LIA (Fig. 12a). Greenland shows an opposite pattern, indicating an increase of annual total precipitation during the MCA. This multiple proxy reconstruction has a limited spatial coverage in the Arctic, so that hydroclimate variability can only be shown for Fennoscandia and part of Greenland. The 3-model ensemble mean shows a different spatial pattern from that of the reconstruction (Fig. 12b), with increasing precipitation over most of Fennoscandia and eastern Greenland. The discrepancy between the reconstruction and the model ensemble mean is not caused by anomalous outputs by any single model but a combination of all the models (Fig. S1); the individual models show differences in spatial patterns compared to the reconstruction. Caution needs to be advised, since the magnitudes of the differences in proxy-derived hydroclimate between the MCA and LIA is consistently larger than in the model ensemble mean or in the individual model simulations. However, the discrepancy between models and proxies may imply that the changes in spatial hydroclimate patterns from the MCA to the LIA over Fennoscandia and Greenland are not related to changes in external forcings, but possibly by internal variability. Another reason for the discrepancy between the reconstruction and the model simulations could be inadequate spatiotemporal availability of proxies across the Arctic, making it unsuitable to investigate changes in the spatial precipitation patterns between the MCA and the LIA. Hence, proxy-based hydroclimate reconstructions covering a wider area of the Arctic are needed in order to make a comprehensive model-data comparison, and further to investigate changes in spatial patterns of Arctic hydroclimate variability and their causes.

The new hydroclimate mean record shows quite coherent variability with L16 on centennial-scales (Fig. 13), especially during the early MCA (*ca*. 900-1200) and early LIA (*ca*. 1400-1600). This is not surprising since they are based on many of the same proxy data. However, the new record suggest a shorter period of wet anomalies during the MCA compared to L16, and the variance of the new hydroclimate mean record is much larger after ca 1200 CE. At a multi-centennial scale, the proxy based reconstructions and model simulations all show drying from 800-1250CE, increasing moisture until ~1500-1600CE, and low values from 1600-1850 CE. Compared to the model simulations, there is a discrepancy with the multi-proxy records during the later part of the MCA, where the model ensemble mean suggests a prolonged wet period, lasting until 1200 CE, compared to the proxy-based records. One of the distinct features in the new hydroclimate mean record is the two distinct wetting anomalies between 1400 and 1600 CE, which are more prominent than in the model simulation and where the latter anomaly is not present in L16. Overall, there is a better agreement between the model simulations and the new hydroclimate mean from the 14th century and onwards compared to L16.

6. Arctic hydroclimate variability in the past 2000 years

6.1. Current understanding

As has been shown in this review, significant efforts have been made to increase our understanding of hydroclimate variability in the Arctic region over the last several decades. However, it is also evident that the available records are insufficient to fully represent such a hydroclimatically inhomogeneous region. Moreover, there are still uncertainties regarding the temporal representation of some proxies and the interpretation of the hydroclimate information, as well as the season that is recorded by the records.

Over the last 1200 years, a commonly studied period as it includes the MCA and the LIA, the proxy reconstructions do not provide clear evidence of systematic hydroclimate patterns across the Arctic or even regionally. In general, drier conditions during the MCA are indicated in several records in Fennoscandia (Fig. 7) and Arctic Canada (Fig. 6), but not across the North American boreal zone (Fig. 5). Similarly, the LIA seems to have been a generally wet period, as indicated by the regional comparisons and evidence of glacier advances (see section 3.4), but again the picture is far from clear. The new Arctic hydroclimate mean synthesis (Fig 13) suggests drying during the MCA, but wet conditions in the early part of the LIA and drier conditions in the latter part. This is largely in agreement with L16, although the latter shows less variability during the mainly dry LIA. At least from the LIA and onwards, there is a better agreement between the model ensemble mean and the new synthesis than with L16. Both Arctic hydroclimate records derived from L16 and the composite presented here are, however, insufficient for drawing any firm conclusions for the whole region.

Hydroclimatic variations during the first millennium CE have received relatively less attention than the MCA and LIA. Detailing the hydroclimate variability of the entire Common Era would allow the placement of the 20th and 21st century changes in a long-term perspective. The Fennoscandian proxy series highlighted a phase of anomalous pre-MCA hydroclimate conditions during the Dark Ages Cold Period. As recently discussed (Helama et al., 2017b), this was possibly a period of noticeable climatic fluctuations, not only in temperature but also in other climatic/environmental variables including hydroclimate. Our results highlight the need for extending the proxy records to cover this climatic period.

Arctic hydroclimate proxies provide information for different target seasons, and this is likely to have an impact on any syntheses. Figure 14a shows the 20th century trends in seasonal Arctic precipitation from the ERA-20C reanalysis data (Poli et al., 2013). The trends are positive in all seasons, but most pronounced in autumn. The greatest precipitation increase occurred over the North Atlantic and Pacific Oceans in all seasons (Fig. 14b), and also over the Arctic Ocean. The changes over land are less coherent in both North America and Eurasia, especially in summer, the target season for many proxies. Regional differences are also evident in a millennium model perspective (Fig. S2). From 900-1900 CE, the model ensemble mean does not show any trends in precipitation, except for a negative trend during autumn (Fig. S2a). Moreover, regional differences in long-term trends are indicated both within regions and between seasons in the three studied models (Fig. S2b). The implication of this is that in order to provide an average view of hydroclimate variability for the Arctic, there must be an even distribution of high-quality, numerically calibrated, verified and replicated climate-sensitive records. However, given current spatial differences in record distribution, it is arguably more valuable to highlight these areas too. More attention should also be paid to the target season of the climate signal when developing large-scale composites to avoid mixing of hydroclimate information across the seasons.

6.2. Towards better understanding of spatiotemporal hydroclimate variability in the Arctic

Spatially explicit hydroclimate reconstructions provide excellent opportunities to study spatiotemporal variations, influences of forcings (e.g. Seager et al., 2007) and for proxy-model comparisons. However, due to the low number of available hydroclimate proxy records from the Arctic, and the imbalance in spatial coverage (Table 3, Fig. 12), it is currently impossible to prepare a field reconstruction for the whole region. As noted in section 3.3, there exist two tree-ring drought atlases covering parts of the Arctic (Fig. 3), however, the data representation is limited and the usage of temperature sensitive tree-ring proxies as hydroclimate indicators need to be properly addressed. Given the precipitation sensitivity of some high-latitude trees (St George and Ault, 2014), as well as more efforts in utilizing isotope records from trees, it may be possible to extend any analyses of hydroclimate variability into Eurasia. Targeted regional spatial reconstructions could be achieved for well-replicated regions, such as Fennoscandia, the Nordic Sea region, or western North America. To facilitate a compilation of Arctic hydrocliamte variability, a dedicated hydroclimate proxy database needs to be developed with firm criteria for which records to include. It is encouraging that several new hydroclimate records have been made available during the process of preparing this review (see Table 2). Moreover, the new synthesis presented in section 5.1 shows the potential to provide regional hydroclimate records with high temporal resolution, providing useful information on multi-decadal timescales (e.g. Fig. 13).

7. Recommendations for future work

- Increase the spatial coverage of hydroclimate proxies. This is particularly important for Eurasia (except Fennoscandia) and North America.
- Several hydroclimate records that would add valuable information are not publicly available, so it is important to encourage palaeoclimate researchers to share and to publicly archive their data.

- Assemble a proper Arctic2k hydro database, where the first step would be to develop criteria for which records to include as guided by priority research goals, taking into consideration the seasonalities in the proxies as an important next step toward a robust and defendable synthesis.
- Consolidate data and attempt to make a field reconstruction for regions with sufficient number of hydroclimate proxy records in time and space. Presently there seems to be opportunities for a trans-Atlantic comparison, which may shed light onto observed regional hydroclimate patterns and the mechanisms behind those.
- Closer collaboration with the palaeoclimate modelling community. From the comparison between the existing "observational" data (reanalysis and proxies) and climate model simulations, discrepancies as well as similarities in both rate and spatial distribution were evident, and this needs to be addressed (Smerdon et al. 2017).

Data availability

The the raw CMIP5/PMIP3 climate data used in this paper can be obtained from http://cmippcmdi.llnl.gov/cmip5/data_getting_started.html, and the specific analyses presented here (Figs. 1-2, 12-14 and S1-2) are available at https://arctic2kpeng.wixsite.com/publicdata. The drought atlases (NADA and OWDA, Fig. 5) are accessible through https://www.ncdc.noaa.gov/paleo/study/6319 (NADA) and https://www.ncdc.noaa.gov/paleo/study/19419 (OWDA). For the accessability of the data presented in Figures 6 and 7, see Table 2. The data described and partly used for the compilation of the Pan-Arctic hydroclimate mean in section 5 are available from the following sources (see text for references): doi:10.5194/cp-10-1605-2014-supplement and https://www.ncdc.noaa.gov/paleo-search/study/19725, doi:10.1594/PANGEA.849161. The synthesis presented in figures 9 (Pan-Arctic) and 11 (North Atlantic and Alaska) are archived on Figureshare and available at: https://figshare.com/articles/Global_North_Atlantic_Alaska_synthesis_record_txt/5502199 (DOI: 10.6084/m9.figshare.5502199).

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References

Aagaard, K. and Carmack, E. C.: The role of sea ice and other fresh water in the Arctic circulation, J. Geophys. Res. 94, 14485–14498, doi:10.1029/JC094iC10p14485, 1989.

Abbott, M. B. and Stafford Jr, T. W.: Radiocarbon geochemistry of modern and Ancient Arctic lake systems, Baffin Island, Canada, Quat. Res., 45, 300-311, doi:10.1006/qres.1996.0031, 1996.

ACIA: Arctic Climate Impact Assessment. Cambridge University Press, 1042p, 2005.

Allen, J. R., Long, A. J., Ottley, C. J., Pearson, D. G. and Huntley, B.: Holocene climate variability in northernmost Europe, Quat. Sci. Rev., 26, 1432-1453, doi:10.1016/j.quascirev.2007.02.009, 2007.

Anchukaitis, K. J., D'Arrigo, R., Andreu-Hayles, L., Frank, D., Verstege, A., Curtis, A., Buckley, B. M., Jacoby, G. C. and Cook, E. R.: Tree-ring reconstructed summer temperatures from north-west North America during the past nine centuries, J. Clim., 26, 3001–3012, doi:10.1175/JCLI-D-11-00139.1, 2013.

Andersen, K. K., Ditlevsen, P. D., Rasmussen, S. O., Clausen, H. B., Vinther, B. M., Johnsen, S. J. and Steffensen, J. P.: Retrieving a common accumulation record from Greenland ice cores for the past 1800 years, J. Geophys. Res. Atm., 111(D15), doi:10.1029/2005JD006765, 2006.

Anderson, L., Abbott, M. B., Finney, B. P. and Burns, S. J.: Late Holocene moisture balance variability in the southwest Yukon Territory, Canada, Quat. Sci. Rev., 26, 130-141, DOI: 10.1016/j.quascirev.2006.04.011, 2007.

Anderson, N. J., Liversidge, A. C., McGowan, S. and Jones, M. D.: Lake and catchment response to Holocene environmental change: spatial variability along a climate gradient in southwest Greenland, J. Paleolimnol., 48, 209-222, doi:10.1007/s10933-012-9616-3, 2012.

Andersson, S. and Schoning, K.: Surface wetness and mire development during the late Holocene in central Sweden, Boreas, 39, 749–760, doi:10.1111/j.1502-3885.2010.00157.x, 2010.

Andresen, C. S., Björck, S., Bennike, O. and Bond, G.: Holocene climate changes in southern Greenland: evidence from lake sediments, J. Quat. Sci., 19, 783-795, doi:10.1002/jqs.886, 2004.

Appenzeller, C., Schwander, J., Sommer, S. and Stocker, T. F.: The North Atlantic Oscillation and its imprint on precipitation and ice accumulation in Greenland, Geophys. Res. Lett., 25, 1939–1942, doi:10.1029/98GL01227, 1998.

Armstrong, R. A.: Lichens, lichenometry and global warming, Microbiologist, 5, 32–35, 2004.

Axford, Y., Geirsdóttir, Á., Miller, G. H. and Langdon, P. G.: Climate of the Little Ice Age and the past 2000 years in northeast Iceland inferred from chironomids and other lake sediment proxies, J. Palaeolimnol., 41, 7–24, doi:10.1007/s10933-008-9251-1, 2009.

Baker, A., Hellstrom, J. C., Kelly, B. F. J., Mariethoz, G., and Trouet, V.: A composite annual-resolution stalagmite record of North Atlantic climate over the last three millennia, Sci. Rep., 5, 10307, doi:10.1038/srep10307, 2015.

Bakke, J., Lie, Ø., Dahl, S.O., Nesje, A., Bjune, A., Strength and spatial patterns of the Holocene wintertime westerlies in the NE Atlantic region. Global Planet Change, 60, 28–41, doi:10.1016/j.gloplacha.2006.07.030, 2008.

Balascio, N. L. and Bradley, R. S.: Evaluating Holocene climate change in northern Norway using sediment records from two contrasting lake systems, J. Paleolimnol., 48, 259-273, doi:10.1007/s10933-012-9604-7, 2012.

Balascio, N. L., D'Andrea, W. J., Gjerde, M. and Bakke, J. (2017) Hydroclimate variability of High Arctic Svalbard during the Holocene inferred from hydrogen isotopes of leaf waxes, Quat. Sci. Rev., doi:10.1016/j.quatscirev.2016.11.036, 2017.

Balascio, N.L., D’Andrea, W.J. and Bradley, R.S.: Glacier response to North Atlantic climate variability during the Holocene, Clim. Past, 11, 1587-1598, doi:10.5194/cp-11-1587-2015, 2015.

Barber, K. E., Chambers, F. M., Maddy, D., Stoneman, R. and Brew, J.: A sensitive high-resolution record of late-Holocene climatic change from a raised bog in northern England, Holocene 4, 198–205, doi:10.1177/095968369400400209, 1994.

Barber, K.E., Dumayne-Peaty, L., Hughes, P. D. M., Mauquoy, D. and Scaife, R. G.: Replicability and variability of the recent macrofossil and proxy-climate record from raised bogs: field stratigraphy and macrofossil data from Bolton Fell Moss and Walton Moss, Cumbria, England, J. Quat. Sci., 13, 515–528, doi:10.1002/(SICI)1099-1417(1998110)13:6<515::AID-JQS393>3.0.CO;2-S ,1998.

Barber, V. A., Juday, G. P., Finney, B. P. and Wilmking, M.: Reconstruction of summer temperatures in interior Alaska from tree-ring proxies: evidence for changing synoptic climate regimes, Climatic Change, 63, 91–120, doi:10.1023/B:CLIM.0000018501.98266.55, 2004.

Barbour, M. M., Andrews, T. J. and Farquhar, G. D.: Correlations between oxygen isotope ratios of wood constituents of Quercus and Pinus samples from around the world, Funct. Plant Biol., 28, 335–348, doi:10.1071/PP00083, 2001.

Barley, E. M., Walker, I. R., Kurek, J. Cwynar, L. C., Mathewes, R. W. Gajewski, K. and Finney, B. P.: A northwest North American training set: distribution of freshwater midges in relation to air temperature and lake depth, J. Palaeolimnol., 36, 295–314, doi:10.1007/s10933-006-0014-6, 2006.

Beilman, D. W., MacDonald, G. M., Smith, L. C. and Reimer P. J.: Carbon accumulation in peatlands of West Siberia over the last 2000 years, Global Biogeochem. Cycles, 23, GB1012, doi:10.1029/2007GB003112, 2009.

Bekryaev, R. V., Ployakov, I. V. and Alexeev, V. A.: Role of Polar Amplification in Long-Term Surface Air Temperature Variations and Modern Arctic Warming, J. Clim., 23, 3888–3906, doi:10.1175/2010JCLI3297.1, 2010.

Belyea, L. R., and Baird A. J.: Beyond “the limits to peat bog growth”: Cross-scale feedback in peatland development, Ecol. Monogr., 76, 299–322, doi:10.1890/0012-9615(2006)076[0299:BTLTPB]2.0.CO;2, 2006.

Berntsson, A., Jansson, K. N., Kylander, M. E., De Vleeschouwer, F. and Bertrand, S.: Late Holocene high precipitation events recorded in lake sediments and catchment geomorphology, Lake Vuoksjávrátje, NW Sweden, Boreas, 44, 676–692, doi:10.1111/bor.12127, 2015.

Bickerton, R. W. and Matthews, J. A.: On the accuracy of lichenometric dates: an assessment based on the 'Little Ice Age' moraine sequence of Nigardsbreen, southern Norway, Holocene, 2, 227 – 237, doi:10.1177/095968369200200304, 1992.

Bintanja, R. and Selten, F. M.: Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat, Nature, 509, 479–482, doi:10.1038/nature13259, 2014.

Birks, S. J. and Edwards, T. W. D.: Atmospheric circulation controls on precipitation isotope–climate relations in western Canada, Tellus, 61B, 566–576, doi:0.1111/j.1600-0889.2009.00423.x, 2009.

Björnsson, H., Pálsson, F., Guðmundsson, S., Magnússon, E., Aðalgeirsdóttir, G., Jóhannesson, T., Berthier, E., Sigurðsson, O., Thorsteinsson, Th.: Contribution of Icelandic ice caps to sea level rise: trends and variability since the Little Ice Age, Geophys. Res. Lett., 40, 1546–1550, doi:10.1002/grl.50278, 2013.

Blackford, J. J. and Chambers, F. M.: Proxy records of climate from blanket mires: Evidence for a Dark Age (1400 BP) climatic deterioration in the British Isles, Holocene, 1, 63–67, doi:10.1177/095968369100100108, 1991.

Blackford, J.: Palaeoclimatic records from peat bogs, Trends Ecol. Evol., 15, 193–198, doi:10.1016/S0169-5347(00)01826-7, 2000.

Boettger, T. and Friedrich, M.: A new serial pooling method of shifted tree ring blocks to construct millennia long tree ring isotope chronologies with annual resolution, Isot. Environ. Healt. S., 45, 68–80, doi:10.1080/10256010802522218, 2009.

Boettger, T., Hiller, A. and Kremenetski, C.: Mid-Holocene warming in northwest Kola Peninsula, Russia: northern pine limit movement and stable isotope evidence, Holocene, 13, 405–412, doi:10.1191/0959683603hl633rp, 2003.

Boldt, B. R., Kaufman, D. S., McKay, N. P., Briner, J. P.. Holocene summer temperature reconstructions from sedimentary chlorophyll content, with treatment of age uncertainties, Kurupa Lake, Arctic Alaska, Holocene, 25, 641–650, doi:10.1177/0959683614565929, 2015.

Boldt, B.R.: A multi-proxy approach to reconstructing Holocene climate variability at Kurupa River valley, Arctic Alaska, Master’s Thesis, Northern Arizona University, 114 pp. 2013.

Booth, R. K., Notaro, M., Jackson, S. T. and Kutzbach, J.E.: Widespread drought episodes in the western Great Lakes region during the past 2000 years: geographic extent and potential mechanisms, Earth Planet. Sc. Lett., 242, 415–427, doi:10.1016/j.epsl.2005.12.028, 2006.

Borgmark, A. and Wastegård, S.: Regional and local patterns of peat humification in three raised peat bogs in Värmland, south-central Sweden. GFF, 130, 161-176, doi:10.1080/11035890809453231, 2008.

Borgmark, A.: Holocene climatic variability and periodicities in south-central Sweden, as interpreted from peat humification analysis, Holocene, 15, 387–395, doi:10.1191/0959683605hl816rp, 2005.

Bowen, G. J.: Isoscapes: Spatial Pattern in Isotopic Biogeochemistry, Annu. Rev. Earth Planet. Sci., 38,161–87, doi:10.1146/annurev-earth-040809-152429, 2010.

Box, J. E., Cressie, N., Bromwich, D., Jung, J., van den Broeke, M., van Angelen, J., Forster, R., Miège, C., Mosley-Thompson, E., Vinther, B. and McConnell, J.: Greenland Ice Sheet Mass Balance Reconstruction. Part I: Net Snow Accumulation (1600–2009), J. Climate, 26, 3919–3934, doi:10.1175/JCLI-D-12-00373.1, 2013.

Boyle, E. A.: Cool tropical temperatures shift the global $\delta^{18}O$ -T relationship: An explanation for the ice core $\delta^{18}O$ - borehole thermometry conflict?. Geophys. Res. Lett., 24, 273-276, doi:10.1029/97GL00081, 1997.

Braconnot, P., Harrison, S. P., Kageyama, M., Bartlein, P. J., Masson-Delmotte, V., Abe Ouchi, A., Otto-Bliesner, B., and Zhao, Y.: Evaluation of climate models using palaeoclimate data, Nat. Clim. Chang., 2, 417–424 doi:10.1038/NCLIMATE1456, 2012.

Briffa, K. R., Osborn, T. J., Schweingruber, F. H., Jones, P. D., Shiyatov, S. G., Vaganov, E. A.: Tree-ring width and density around the Northern Hemisphere: part 1, local and regional climate signals, Holocene, 12, 737–757, doi:10.1191/0959683602hl587rp, 2002.

Briffa, K. R., Osborn, T. J., Schweingruber, F.H., Harris, I. C., Jones, P. D., Shiyatov, S. G. and Vaganov, E. A. Low-frequency temperature variations from a northern tree-ring density network, J. Geophys. Res., 106, 2929–2941, doi:10.1029/2000JD900617, 2001.

Bring, A., Fedorova, I., Dibike, Y., Hinzman, L., Mård, J., Mernild, S. H., Prowse, T., Semenova, O., Stuefer, S. L. and Woo, M.-K.: Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges, J. Geophys. Res. Biogeosci., 121, 621–649, doi:10.1002/2015JG003131, 2016.

Budikova D.: Role of Arctic sea ice in global atmospheric circulation: A review, Glob. Plan. Chan., 68: 149–163, doi:10.1016/j.gloplacha.2009.04.001, 2009.

Bunbury, J. and Gajewski, K.: Postglacial climates inferred from a lake at treeline, southwest Yukon Territory, Canada, Quat. Sci. Rev., 28: 354-369 doi:10.1016/j.quascirev.2008.10.007, 2009.

Bunbury, J., Finkelstein, S. A. and Bollmann, J.: Holocene hydro-climatic change and effects on carbon accumulation inferred from a peat bog in the Attawapiskat River watershed, Hudson Bay Lowlands, Canada, Quat. Res., 78, 275–284, doi:10.1016/j.yqres.2012.05.013, 2012.

Camill, P., Umbanhowar, C. E., Geiss, C., Hobbs, W. O., Edlund, M. B., Shinneman, A. C., Dorale, J.A. and Lynch, J.: Holocene climate change and landscape development from a low-Arctic tundra lake in the western Hudson Bay region of Manitoba, Canada, J. Paleolimnol., 48, 175-192, doi:10.1007/s10933-012-9619-0, 2012.

Carmack, E. C., Yamamoto-Kawai, M., Haine, T. W. N., Bacon, S., Bluhm, B. A., Lique, C., Melling, H., Polyakov, I. V., Straneo, F., Timmermans, M.-L. and Williams, W. J.: Freshwater and its role in the Arctic Marine System: Sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans, J. Geophys. Res. Biogeosci., 121, 675–717, doi:10.1002/2015JG003140, 2016.

Carmack, E. C., Yamamoto-Kawai, M., Haine, T. W. N., Bacon, S., Bluhm, B. A., Lique, C., Melling, H., Polyakov, I. V., Straneo, F., Timmermans, M.-L. and Williams, W. J.: Freshwater and its role in the Arctic Marine System: Sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans, J. Geophys. Res. Biogeosci., 121, 675–717, doi:10.1002/2015JG003140, 2016.

Carter, R., LeRoy, S., Nelson, T., Laroque, C.P., Smith, D.J.: Dendroglaciological investigations at Hilda Creek rock glacier, Banff National Park, Canadian Rocky Mountains, Géogr. Phys. Quat., 53, 365–371, doi:10.7202/004777ar, 1999.

Chambers, F. M., Beilman, D.W., Yu, Z.: Methods for determining peat humification and for quantifying peat bulk density, organic matter and carbon content for palaeostudies of climate and peatland carbon dynamics, Mires and Peat, 7, Art. 7, (Online: http://www.mires-and-peat.net/pages/volumes/map07/map0707.php), 2011.

Chapligin, B., Narancic, B., Meyer, H. and Pienitz, R.: Palaeo-environmental gateways in the eastern Canadian Arctic - recent isotope hydrology and diatom oxygen isotopes from Nettilling Lake, Baffin Island, Canada, Quat. Sci. Rev. 147, 379–90. doi:10.1016/j.quascirev.2016.03.028, 2016.

Charman, D. J., Barber, K. E., Blaauw, M., Langdon, P. G., Mauquoy, D., Daley, T. J., Hughes, P. D. M. and Karofeld, E.: Climate drivers for peatland palaeoclimate records, Quat. Sci. Rev. 28, 1811–1819, doi:10.1016/j.quascirev.2009.05.013, 2009.

Charman, D. J., Hendon, D., Woodland, W. A.: The Identification of Testate Amoebae (Protozoa: Rhizopoda) in Peats, Technical Guide No. 9, Quaternary Research Association, London, 147 pp, 2000.

Charman, D. J.: Summer water deficit variability controls on peatland water-table changes: implications for Holocene palaeoclimate reconstructions, Holocene 17, 217–227, doi:10.1177/0959683607075836, 2007.

Charman, D., Beilman, D., Blaauw, M., Booth, R. K., Brewer, S., Chambers, F., Christen, J. A., Gallego-Sala, A. V., Harrison, S. P., Hughes, P. D. M., Jackson, S., Korhola, A., Mauquoy, D., Mitchell, F., Prentice, I. C., van der Linden, M., De Vleeschouwer, F., Yu, Z., Alm, J., Bauer, I. E., McCorish, Y., Garneau, M., Hohl, V., Huang, Y., Karofeld, E., Le Roux, G., Loisel, J., Moschen, R., Nichols, J. E., Nieminen, T. M., MacDonald, G. M., Phadtare, N. R., Rausch, N., Sillasoo, Ü., Swindles, G. T., Tuittila, E.-S., Ukonmaanaho, L., Väliranta, M., van Bellen, S., van Geel, B., Vitt, D., and Zhao, Y.: Climate-related changes in peatland carbon accumulation during the last millennium, Biogeosciences, 10, 929–944, doi:10.5194/bg-10-929-2013, 2013.

Charman, D.: Peatlands and Environmental Change. John Wiley & Sons, Chichester, 312 pp, 2002.

Chipman, M. L., Clarke, G. H., Clegg, B. F., Gregory-Eaves, I. and Hu, F. S.: (2009). A 2000 year record of climatic change at Ongoke Lake, southwest Alaska, J. Paleolimnol., 41, 57-75, doi:10.1007/s10933-008-9257-8, 2009.

Clegg, B. F. and Hu, F. S.: An oxygen-isotope record of Holocene climate change in the south-central Brooks Range, Alaska, Quat. Sci. Rev., 29, 928-939, doi:10.1016/j.quascirev.2009.12.009, 2010.

Clymo, R. S.: The limits to peat bog growth, Philos. Trans. R. Soc. Lond. B. Biol. Sci., 303, 605–654, doi:10.1098/rstb.1984.0002, 1984.

Cohen, J., Furtado, J. C., Barlow, M. A., Alexeev, V. A. and Cherry, J. E.: Arctic warming, increasing snow cover and widespread boreal winter cooling, Environ. Res. Lett., 7, 014007, doi:10.1088/1748-9326/7/1/014007, 2012.

Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., Francis, J., Dethloff, K., Entekhabi, D., Overland, J., Jones, J.: Recent Arctic amplification and extreme mid-latitude weather, Nat. Geosci. 7, 627–637, doi:10.1038/ngeo2234, 2014.

Cole, G. A., and Marsh, T. J.: The impact of climate change on severe droughts. Major droughts in England and Wales from 1800 and evidence of impact, in Science Report: SC040068/SR1, Environment Agency, Bristol, UK, 2006.

Cook, E. R., Meko, D. M. Stahle, D. W. and Cleaveland, M. K.: Drought reconstructions for the continental United States, J. Clim., 12, 1145–1162, doi:10.1175/1520-0442,1999.

Cook, E. R., Seager, R. Cane, M. A. and Stahle, D. W.: North American drought: Reconstructions, causes and consequences. Earth-Sci. Rev., 81, 93–134, doi:10.1016/j.earscirev.2006.12.002, 2007.

Cook, E.R., Seager, R., Kushnir, Y., Briffa, K.R., Büntgen, U., Frank, D., Krusic, P.J., Tegel, W., van der Schrier, G., Andreu-Hayles, L,. Baillie, M., Baittinger, C., Bleicher, N., Bonde, N., Brown, D., Carrer, M., Cooper, R., Čufar, K., Dittmar, C., Esper, J., Griggs, C., Gunnarson, B., Günther, B., Gutierrez, E., Haneca, K., Helama, S., Herzig, F., Heussner, K.-U., Hofmann, J., Janda, P., Kontic, R., Köse, N., Kyncl, T., Levanič, T., Linderholm, H., Manning, S., Melvin, T.M., Miles, D., Neuwirth, B., Nicolussi, K., Nola, P., Panayotov, M., Popa, I., Rothe, A., Seftigen, K., Seim, A., Svarva, H., Svoboda, M., Thun, T., Timonen, M., Touchan, R., Trotsiuk, V., Trouet, V., Walder, F., Ważny, T., Wilson, R. and Zang, C.: Old World Megadroughts and Pluvials During the Common Era, Science Adv., 1, e1500561, doi:10.1126/sciadv.1500561, 2015.

Cook, E.R., Woodhouse, C. A. Eakin, C. M. Meko, D. M. Stahle, D. W.: Long-term aridity changes in the western United States, Science, 306, 1015–1018, doi:10.1126/science.1102586, 2004.

Courtney-Mustaphi, C. and Gajewski, K.: Holocene sediments from a coastal lake on northern Devon Island, Nunavut, Canada, Can. J. Earth Sci., 50, 564–575, doi:10.1139/cjes-2012-0143, 2013.

Csank, A. Z. Patterson, W. P., Eglington, B. M. Rybczynski, N. and Basinger, J.F.: Climate variability in the Early Pliocene Arctic: Annually resolved evidence from stable isotope values of sub-fossil wood, Ellesmere Island, Canada. Palaeogeogr. Palaeoclimatol. Palaeoecol., 308, 339–349, doi:10.1016/j.palaeo.2011.05.038, 2011.

Cuven, S., Francus, P. and Lamoureux, S. F.: Estimation of grain size variability with micro X-ray fluorescence in laminated lacustrine sediments, Cape Bounty, Canadian High Arctic, J. Paleolimnol., 44, 803-817, doi: 10.1007/s10933-010-9453-1, 2010.

Cuven, S., Francus, P. and Lamoureux, S.: Mid to Late Holocene hydroclimatic and geochemical records from the varved sediments of East Lake, Cape Bounty, Canadian High Arctic. Quat. Sci. Rev., 30, 2651-2665, doi:10.1016/j.quascirev.2011.05.019, 2011.

Cuven, S., Francus, P. and Lamoureux, S.: Mid to Late Holocene hydroclimatic and geochemical records from the varved sediments of East Lake, Cape Bounty, Canadian High Arctic, Quat. Sci. Rev., 30, 2651-2665, doi:10.1016/j.quascirev.2011.05.019, 2011.

D'Andrea, W. J., Vaillencourt, D. A., Balascio, N. L., Werner, A., Roof, S. R., Retelle, M. and Bradley, R. S.: Mild Little Ice Age and unprecedented recent warmth in an 1800 year lake sediment record from Svalbard, Geology, 40, 1007–1010, doi:10.1130/G33365.1, 2012.

D'Arrigo, R., Wilson, R. and Jacoby, G.: On the long-term context for late twentieth century warming. J. Geophys. Res. 111, D03103, doi:10.1029/2005JD00635, 2006.

Dahl, S. O. and Nesje, A.: A new approach to calculating Holocene winter precipitation by combining glacier equilibrium-line altitudes and pine-tree limits: a case study from Hardangerjøkulen, central southern Norway, Holocene, 6, 381–398, doi:10.1177/095968369600600401, 1996.

Dahl, S. O. and Nesje, A.: Holocene glacier fluctuations at Hardangerjøkulen, central-southern Norway: a high resolution composite chronology from lacustrine and terrestrial deposits, Holocene 4, 269–277, doi:10.1177/095968369400400306, 1994.

Danis, P. A., Masson-Delmotte, V., Stievenard, M., Guillemin, M. T., Daux, V., Naveau, Ph. and von Grafenstein, U.: Reconstruction of past precipitation δ18O using tree-ring cellulose δ18O and δ13C: a calibration study near Lac d'Annecy, France, Earth Planet. Sc. Lett., 243, 439–448, doi:10.1016/j.epsl.2006.01.023, 2006.

Dansgaard, W.: Stable isotopes in precipitation, Tellus, 16, 436–468, doi:10.1111/j.2153-3490.1964.tb00181.x., 1964.

D'Arrigo, R. D. and Jacoby, G. C.: Secular trends in high northern latitude temperature reconstructions based on tree rings, Clim. Chang., 25, 163–177, doi:10.1007/BF01661204, 1993.

D'Arrigo, R. D. and Jacoby, G. C.: Secular trends in high northern latitude temperature reconstructions based on tree rings, Clim. Chang., 25, 163–177, doi:10.1007/BF01661204, 1993.

Dearing, J., Hu, Y., Doody, P., James, P. A., Brauer, A.: Preliminary reconstruction of sediment-source linkages for the past 6000 yrs at the petit lac d'annecy, france, based on mineral magnetic data, J. Paleolimnol., 25, 245-258, doi:10.1023/A:1008186501993, 2001.

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, Cilm. Past., 3, 569–575, doi:10.5194/cp-3-569-2007, 2007.

Dufresne, J-L., Foujols, M-A., Denvil, S., Caubel, A., Marti, O., Aumont, O., Balkanski, Y., Bekki, S., Bellenger, H., Benshila, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., de Noblet, N., Duvel, J.-P., Ethé, C., Fairhead, L., Fichefet, T., Flavoni, S., Friedlingstein, P., Grandpeix, J-Y., Guez, L., Guilyardi, E., Hauglustaine, D., Hourdin, F., Idelkadi, A., Ghattas, J., Joussaume, S., Kageyama, M., Krinner, G., Labetoulle, S., Lahellec, A., Lefebvre, M-P., Lefevre, F., Levy, C., Li, Z. X., Lloyd, J., Lott, F., Madec, G., Mancip, M., Marchand, M., Masson, S., Meurdesoif, Y., Mignot, J., Musat, I., Parouty, S., Polcher, J., Rio, C., Schulz, M., Swingedouw, D., Szopa, S., Talandier, C., Terray, P., Viovy, N. and Vuichard, N.: Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5, Clim. Dyn., 40, 2123–2165, doi:10.1007/s00382-012-1636-1, 2013.

Edlund, S. A., and P. A. Egginton.: Morphology and Description of an Outlier Population of Tree-Sized Willows on Western Victoria Island, District of Franklin, Geological Survey of Canada, Current Research: Part A, 84, 279–285. 1984

Edvardsson, J. G., Stoffel, M., Corona, C., Bragazza, L., Leuschner, H. H., Charman, D.J., and Helama, S.: Subfossil peatland trees as proxies for Holocene palaeohydrology and palaeoclimate, Earth-Science Rev., 163, 118–140, doi:10.1016/j.earscirev.2016.10.005, 2016.

Esper, J., Cook, E. R., and Schweingruber, F. H.: Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability, Science, 295, 2250–2253, doi:10.1126/science.1066208, 2002.

Fang, K., Gou, X., Chen, F., Cook, E., Li, J., Buckley, B. and D'Arrigo, R.: Large-scale precipitation variability over northwest China inferred from tree rings, J. Clim., 24, 3457–3468, doi:10.1175/2011JCLI3911.1, 2011.

Farquhar, G. D., O'Leary, M. H. and Berry, J. A.: On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration of leaves, Aust. J. Plant Phys., 9, 121–137, doi:10.1071/PP9820121, 1982.

Finkelstein, S. A, Bunbury, J., Gajewski, K., Wolfe, A. P., Adams J. K. and Devlin, J. E.: Evaluating diatom-derived Holocene pH reconstructions for arctic lakes using an expanded 171-lake training set, J. Quat. Sci., 29, 249–260, doi:10.1002/jqs.2697, 2014.

Finney, B. P., Bigelow, N. H., Barber, V. A. and Edwards, M. E.: Holocene climate change and carbon cycling in a groundwater-fed, boreal forest lake: Dune Lake, Alaska, J. Paleolimnol., 48, 43-54, doi:10.1007/s10933-012-9617-2, 2012.

Folland, C. K., Knight, J., Linderholm, H. W., Fereday, D., Ineson, S., and Hurrell J. W.: The summer North Atlantic Oscillation: past, present, and future, J. Clim., 22, 1082–1103, doi:10.1175/2008JCLI2459.1, 2009.

Ford, J. D., McDowell, G. and Jones, J.: The state of climate change adaptation in the Arctic, Environ. Res. Lett., 9, 104005, doi:10.1088/1748-9326/9/10/104005, 2014.

Fortin, M-C., Medeiros, A. S. Gajewski, K. Barley, E. M., Larocque-Tobler, I., Porinchu D. F. and Wilson, S. E. Chironomid-environment relations in northern North America, J. Palaeolimnol., 54, 223–237, doi:10.1007/s10933-015-9848-0, 2015.

Francis, J. A., Chan, W. Leathers, D. J. Miller, J. R. and Veron D. E.: Winter Northern Hemisphere weather patterns remember summer Arctic sea ice extent, Geophys. Res. Lett., 36, L07503, doi:10.1029/2009GL037274, 2009.

Francus, P., Bradley, R. S., Lewis, T., Abbott, M., Retelle, M. and Stoner, J. S.: Limnological and sedimentary processes at Sawtooth Lake, Canadian High Arctic, and their influence on varve formation, J. Paleolimnol., 40, 3: 963-985, doi:10.1007/s10933-008-9210-x, 2008.

Frankenberg, C., Yoshimura, K., Warneke, T., Aben, I., Butz, A., Deutscher, N., Griffith, D., Hase, F., Notholt, J., Schneider, M. and Schrijver, H.: Dynamic processes governing lower-tropospheric HDO/H_2O ratios as observed from space and ground, Science, 325, 1374-1377, doi:10.1126/science.1173791, 2009.

Gagen, M. H., Zorita, E., McCarroll, D., Young, G. H. F., Grudd, H., Jalkanen, R., Loader, N. J, Robertson, I., Kirchhefer, A. J.: Cloud response to summer temperatures in Fennoscandia over the last thousand years, Geophys. Res. Lett., 38, L05701, doi:10.01029/02010GL046216, 2011.

Gajewski, K., Bouchard, G., Wilson, S. Kurek, J. and Cwynar, L.: Distribution of Chironomidae (Insecta: Diptera) head capsules in recent sediments of Canadian Arctic lakes, Hydrobiologia, 549, 131–143, doi:10.1007/s10750-005-5444-z, 2005.

Gajewski, K., Garneau, M., Bourgeois, J.: Paleoenvironments of the Canadian High Arctic derived from pollen and plant macrofossils: problems and potentials. Quat. Sci. Rev., 14, 609-629, doi: 10.1016/0277-3791(95)00015-H, 1995.

Gajewski, K.: Impact of Holocene Climate Variability on Arctic Vegetation, Glob. Planet. Change, 133, 272-287, doi:10.1016/j.gloplacha.2015.09.006, 2015b.

Gajewski, K.: Is Arctic palynology a “blunt instrument”? Geogr. Phy. Quat., 60, 95-102, 2006.

Gajewski, K.: Modern pollen assemblages in lake sediments from the Canadian Arctic. Arct., Ant., Alp. Res., 34, 26-32, doi: 10.2307/1552505, 2002.

Gajewski, K.: Quantitative reconstruction of Holocene temperatures across the Canadian Arctic and Greenland, Glob. Planet. Chang., 128, 14–23, doi:10.1016/j.gloplacha.2015.02.003, 2015a.

Gälman, V., Rydberg, J., De-Luna, S. S., Bindler, R. and Renberg, I.: Carbon and nitrogen loss rates during aging of lake sediment: Changes over 27 years studied in varved lake sediment, Limnol. Oceanogr., 53, 1076-1082, doi:10.4319/lo.2008.53.3.1076, 2008.

Garcin, Y., Schwab, V.F., Gleixner, G., Kahmen, A., Todou, G., Séné, O., Onana, J.M., Achoundong, G. and Sachse, D.: Hydrogen isotope ratios of lacustrine sedimentary n-alkanes as proxies of tropical African hydrology: insights from a calibration transect across Cameroon, Geochim. Cosmochim. Acta, 79, 106-126, doi:10.1016/j.gca.2011.11.039, 2012.

Gastaldo, R.A.: Conspectus of phytotaphonomy. The Palaeontological Society Special Publication, 3, 14–28, 1988.

Gedney, N. Cox, P. M., Betts, R. A. Boucher, O. Huntingford, C. and Stott, P. A.: Detection of a direct carbon dioxide effect in continental river runoff records, Nature, 439, 835–838, doi:10.1038/nature04504, 2006.

Geer, A., Ng, V. and Fisman, D.: Climate change and infectious diseases in North America: the road ahead, Can. Med. Assoc. J., 178, 715-722, doi: 10.1503/cmaj.081325, 2008.

Gessler, A., Pedro Ferrio, J., Hommel, R., Treydte, K., Werner, R.A. Monson, R.K.: Stable isotopes in tree rings: towards a mechanistic understanding of isotope fractionation and mixing processes from the leaves to the wood, Tree Physiol., 34, 796–818. doi:10.1093/treephys/tpu040, 2014.

Gorham, E., Lehman, C., Dyke, A., Janssens, J. and Dyke, L.: Temporal and spatial aspects of peatland initiation following deglaciation in North America, Quat. Sci. Rev., 26, 300–311, doi:10.1016/j.quascirev.2006.08.008, 2007.

Gosse, J. C., Phillips, F. M.: Terrestrial in situ cosmogenic nuclides: theory and application, Quat. Sci. Rev., 20, 1475–1560, doi:10.1016/S0277-3791(00)00171-2, 2001.

Granger, D. E., Lifton, N. A., Willenbring, J. K.: A cosmic trip: 25 years of cosmogenic nuclides on geology, Geol. Soc. Am. Bull., 125, 1379–1402, doi:10.1130/B30774.1, 2013.

Gray, S. T., Betancourt, J. L. Fastie, C. L. and Jackson, S. T.: Patterns and sources of multidecadal oscillations in drought-sensitive tree-ring records from the central and southern Rocky Mountains, Geophys. Res. Lett., 30, 1316, doi:10,1029/2002GL01654, 2003.

Gunnarson, B. E., Borgmark, A., and Wastegård, S.: Holocene humidity fluctuations in Sweden inferred from dendrochronology and peat stratigraphy, Boreas, 32, 347–360, doi:10.1111/j.1502-3885.2003.tb01089.x, 2003.

Gunnarson, B. E.: Temporal distribution pattern of subfossil pines in central Sweden: perspective on Holocene humidity fluctuations, Holocene, 18, 569–577, doi:10.1177/0959683608089211, 2008.

Guo, D., Gao, Y., Bethke, I., Gong, D., Johannessen, O. M., and Wang, H.: Mechanism on how the spring Arctic sea ice impacts the East Asian summer monsoon. Theor. Appl. Climatol., 115, 107–119, doi:10.1007/s00704-013-0872-6, 2014.

Haeberli, W. and Hoelzle, M.: Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps, Ann. Glaciol., 21, 206–212, doi:10.1017/S0260305500015834, 1995.

Hanhijärvi, S., Tingley, M. P. and Korhola, A.: 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.

Hardy, D. R., Bradley, R. S. and Zolitschka, B.: The climatic signal in varved sediments from Lake C2, northern Ellesmere, J. Paleolimnol., 16, 227-238, doi:10.1007/BF00176938, 1996.

Hari, P. and Nöjd, P.: The effect of temperature and PAR on the annual photosynthetic production of Scots pine in northern Finland during 1906–2002. Boreal Env. Res., 14 (suppl. A), 5–18, 2009.

Hassan, U. and Anwar, M. S.: Reducing noise by repetition : introduction to signal averaging, Eur. J. Phys., 31, 453–465, doi: 10.1088/0143-0807/31/3/003, 2010.

Heikkilä, M., Edwards, T. W., Seppä, H. and Sonninen, E.: Sediment isotope tracers from Lake Saarikko, Finland, and implications for Holocene hydroclimatology, Quat. Sci. Rev., 29, 2146-2160, DOI: 10.1016/j.quascirev.2010.05.010, 2010.

Helama, S., and Lindholm, M.: Droughts and rainfall in southeastern Finland since AD 874, inferred from Scots pine ring widths, Boreal Environ. Res., 8, 171–183, 2003.

Helama, S., Arppe, L., Uusitalo, J., Mäkelä, H. M., Oinonen, M. and Mielikäinen, K.: Coexisting responses in tree-ring δ13C to high-latitude climate variability under elevated CO2: A critical examination of climatic effects and systematic discrimination rate changes, Agric. For. Meteorol., 199, 226–227, doi:10.1016/j.agrformet.2016.06.005, 2016.

Helama, S., Eronen, M., and Timonen, M.: Dendroécologie des bois fossiles dans le nord de la Laponie, In: La Dendroécologie: Principes, méthodes et applications, [Payette, S. and Filion, L. (eds.)], Presses de l'Université Laval, Québec, Québec, 709–730, 2010.

Helama, S., Jones, P. D. and Briffa, K. R.: Dark Ages Cold Period: A literature review and directions for future research, Holocene, doi:10.1177/0959683617693898, 2017b.

Helama, S., Jones, P.D. and Briffa K.R.: Limited Late Antique cooling. Nature Geosci., 10, 242–243, doi:10.1038/ngeo2926, 2017c.

Helama, S., Lindholm, M., Timonen, M., and Eronen, M.: Mid- and late Holocene tree population density changes in northern Fennoscandia derived by a new method using megafossil pines and their tree-ring series, J. Quat. Sci., 20, 567–575, doi:10.1002/jqs.929, 2005.

Helama, S., Luoto, T. P., Nevalainen, L., and Edvardsson, J.: Rereading a tree-ring database to illustrate depositional histories of subfossil trees, Palaeontol. Electronica, 20, 1–12, 2017a.

Helama, S., Merilainen, J. and Tuomenvirta, H.: Multicentennial megadrought in northern Europe coincided with a global El Niño–Southern Oscillation drought pattern during the Mediaeval Climate Anomaly, Geology, 37, 175–178, doi:10.1130/G25329A.1, 2009.

Helama, S., Meriläinen, J. and Tuomenvirta, H.: Multicentennial megadrought in northern Europe coincided with a global El Niño–Southern Oscillation drought pattern during the Medieval Climate Anomaly, Geology, 37, 175-178, doi: 10.1130/G25329A, 2009.

Helama, S., Sohar, K., Läänelaid, K., Bijak, S. and Jaagus, J.: Reconstruction of precipitation variability in Estonia since the eighteenth century, inferred from oak and spruce tree rings, Clim. Dyn., doi: 10.1007/s00382-017-3862-z. 2017d.

Hellmann, L., Agafonov, L., Ljungqvist, F.C., Churakova, O., Düthorn, E., Esper, J., Hülsmann, L., Kirdyanov. A.V., Moisev, P., Myglan, W.S., Nikolaev, A.N., Reinig, F., Schweingruber, F.H., Solomina, O., Tegel, W. and Büntgen, U.: Diverse growth trends and climate responses across Eurasia's boreal forest, Environ. Res. Lett., 11, 074021, doi: 0.1088/1748-9326/11/7/074021, 2016.

Hemming D., Griffiths, H., Loader, N. J., Marca, A., Robertson, I., Williams, D., Wingate, L. and Yakir, D.: The future of large scale stable isotope networks, Terrest. Ecol., 1, 361–381, doi:10.1016/S1936-7961(07)01023-8, 2007.

Henderson, K. A.: An ice core palaeoclimate study of Windy Dome, Franz Josef Land, Russia: development of a recent climate history for the Barents Sea, PhD thesis, Ohio State University. Columbus, Ohio, 218 pp., 2002.

Hendon, D., Charman, D. J., Kent, M.: Palaeohydrological records derived from testate amoebae analysis from peatlands in northern England: within-site variability, between-site comparability and palaeoclimatic implications, Holocene 11, 127–148, doi:10.1191/095968301674575645, 2001.

Hilasvuori, E. and Berninger, F.: Dependence of tree ring stable isotope abundances and ring width on climate in Finnish oak, Tree Physiol., 30, 636–647, doi:10.1093/treephys/tpq019, 2010.

Hilbert, D.W., Roulet, N. and Moore, T.: Modelling and analysis of peatlands as dynamical systems, J. Ecol., 88, 230–242, doi:10.1046/j.1365-2745.2000.00438.x, 2000.

Hind, A., Zhang, Q., and Brattström, G.: Problems encountered when defining Arctic amplification as a ratio, Scientific Reports, 6, 30469, doi: 10.1038/ srep30469, 2016.

Holzkämper, S., Kuhry, P., Kultti, S., Gunnarson, B. and Sonninen, E.: Stable isotopes in tree rings as proxies for winter precipitation changes in the Russian arctic over the past 150 years, Geochronometria 32, 37–46, doi:10.2478/v10003-008-0025-6, 2008.

Holzkämper, S., Tillman, P.K., Khury, P. and Esper, J.: Comparison of stable carbon and oxygen isotopes in Picea glauca tree rings and Sphagnum fuscum moss remains from subarctic Canada, Quat. Res., 78, 295–302, doi:10.1016/j.yqres.2012.05.014, 2012.

Hou, J., D'Andrea, W. J. and Huang, Y.: Can sedimentary leaf waxes record D/H ratios of continental precipitation? Field, model, and experimental assessments, Geochim. Cosmochim. Acta,72, 3503-3517, doi:10.1016/j.gca.2008.04.030, 2008.

Hua, T., Wang, X. M., Zhang, C. X. and Lang, L. L.: Temporal and spatial variations in the Palmer Drought Severity Index over the past four centuries in arid, semiarid, and semihumid East Asia, Chin. Sci. Bull., 58, 4143–4152, doi:10.1007/s11434-013-5959-z, 2013.

Huang, Y., Shuman, B., Wang, Y. and Webb, T.: Hydrogen isotope ratios of individual lipids in lake sediments as novel tracers of climatic and environmental change: a surface sediment test, J. Paleolimnol., 31, 363-375, doi:10.1023/B:JOPL.0000021855.80535.13, 2004.

Hughes, P. D. M., Mauquoy, D., Barber, K. E. and Langdon, P. G.: Mire-development pathways and palaeoclimatic records from a full Holocene peat archive at Walton Moss, Cumbria, England, Holocene, 10, 465–79, doi:10.1191/095968300675142023, 2000.

Humlum, O., Elberling, B., Hormes, A., Fjordheim, K., Hansen, O.H., Heinemeier, J., Late-Holocene glacier growth in Svalbard, documented by subglacial relict vegetation and living soil microbes, Holocene, 15, 396–407, doi:10.1191/0959683605hl817rp, 2005.

Huntington, T. G.: Evidence for intensification of the global water cycle: Review and synthesis, J. Hydrol., 319, 83–95, doi:10.1016/j.jhydrol.2005.07.003, 2006.

Hurrell, J.W.: Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation, Science, 269, 676–679, doi:10.1126/science.269.5224.676, 1995.

IPCC: Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M.

Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013

Itkonen, A. and Salonen, V-P.: The response of sedimentation in three varved lacustrine sequences to air temperature, precipitation and human impact, J. Paleolimnol., 11, 323-332, doi:10.1007/BF00677992, 1994.

Jahren, A. H. and Sternberg, L. S. L.: Annual patterns within tree rings of the Arctic middle Eocene (ca. 45 Ma): Isotopic signatures of precipitation, relative humidity and deciduousness, Geology, 36, 99–102, doi:10.1130/G23876A.1, 2008.

Janbu, A. D., Paasche, Ø. and Talbot, M. R.: Paleoclimate changes inferred from stable isotopes and magnetic properties of organic-rich lake sediments in Arctic Norway, J. Paleolimnol., 46, 29-44, doi:10.1007/s10933-011-9512-2, 2011.

Johannessen, O. M., Miles, M. W., Bengtsson, L., Bobylev, L. P. and Kuzmina, S. I.: Arctic climate change, In: Arctic Environment Variability in the Context of Global Change [Bobylerv, P. K., Kondratyev, K. Y. and Johannessen, O.M. (eds.)], 1–15, 2003.

Jones, P. D., Briffa, K. R., Barnett, T. P. and Tett, S. F. B.: High resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with general circulation model control-run temperatures, Holocene, 8, 455–471, doi:10.1191/095968398667194956, 1998.

Jönsson, K., and Nilsson, C.: Scots pine (Pinus sylvestris L.) on shingle fields: A dendrochronologic reconstruction of early summer precipitation in mideast Sweden, J. Clim., 22, 4710– 4722, doi:10.1175/2009JCLI2401.1, 2009.

Jungclaus, J. H., Lohmann, K., and Zanchettin, D.: Enhanced 20thcentury heat transfer to the Arctic simulated in the context of climate variations over the last millennium, Clim. Past, 10, 2201– 2213, doi:10.5194/cp-10-2201-2014, 2014.

Karlén, W. and Denton. G. H.: Holocene glacial variations in Sarek National Park, northern Sweden, Boreas, 5, 25–56, doi:10.1111/j.1502-3885.1976.tb00329.x, 1976.

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., Arctic Lakes 2k Project Members.: Recent warming reverses long-term Arctic cooling, Science, 325, 1236–1239, doi:10.1126/science.1173983, 2009.

Keisling, B. A., Castañeda, I. S. and Brigham-Grette, J.: Hydrological and temperature change in Arctic Siberia during the intensification of Northern Hemisphere Glaciation, Earth Plan. Sci. Lett., 457, 136–148, doi:10.1016/j.epsl.2016.09.058, 2017.

Kelly, P. M., Jones, P. D., Sear, B. C. B., Cherry, S. G. and Tavakol, R. K.: Variations in Surface Air Temperatures: Part 2. Arctic Regions, 1881–1980, Month. Weath. Rev., 110, 71–83, doi: 10.1175/1520-0493(1982)110<0071:VISATP>2.0.CO;2, 1982.

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

Kirkbride, M. P., Dugmore, A. J.: Responses of mountain lee caps in central Iceland to Holocene climate change, Quat. Sci. Rev., 25, 1692–1707, doi:10.1016/j.quascirev.2005.12.004, 2006.

Knorre, A. A., Siegwolf, R. T. W., Saurer, M., Sidorova, O. V., Vaganov, E. A., Kirdyanov, A. V.: Twentieth century trends in tree ring stable isotopes (δ13C and δ18O) of Larix sibirica under dry conditions in the forest steppe in Siberia, J. Geophys.Res., 115, G03002, doi:10.1029/2009JG000930, 2010.

Koch, J., Clague, J. J.: Extensive glaciers in northwest North America during Mediaeval time, Clim. Chang., 107, 593–613, doi:10.1007/s10584-010-0016-2, 2011.

Koerner, R. M.: Mass balance of glaciers in the Queen Elizabeth Islands, Nunavut, Canada, Ann. Glaciol., 42, 417–423, doi:10.3189/172756405781813122, 2005.

Kopec, B. G, Feng, X., Michel, F. A. and Posmentier, E. S.: Influence of sea ice on Arctic precipitation, Proc. Natl. Acad. Sci. U.S.A., 113, 46–51, doi:10.1073/pnas.1504633113, 2016.

Korhola, A.: The Early Holocene hydrosere in a small acid hill-top basin studied using crustacean sedimentary remains, J. Palaeolimnol., 7, 1–22, doi:10.1007/BF00197028, 1992.

Kremenetski, K. V., Boettger, T., MacDonald, G. M., Vaschalova, T., Sulerzhitsky, L. and Hiller, A.: Mediaeval climate warming and aridity as indicated by multiproxy evidence from the Kola Peninsula, Russia, Palaeogeogr. Palaeoclimatol. Palaeoecol., 209, 113–125, doi:10.1016/j.palaeo.2004.02.018, 2004.

Kress, A., Young, G. H. F., Saurer, M., Loader, N. J., Siegwolf, R. T. W. and McCarroll, D.: Stable isotope coherence in the earlywood and latewood of tree-line conifers, Chem. Geol., 268, 52–57, doi:10.1016/j.chemgeo.2009.07.008, 2009.

Kwok, R. and Cunningham, G. F.: Variability of Arctic sea ice thickness and volume from CryoSat-2, Phil. Trans. R. Soc. A, 373, 20140157, doi:10.1098/rsta.2014.0157, 2015

Labuhn, I., Daux, V., Pierre, M., Stievenard, M., Girardclos, O., Feŕon, A., Genty, D., Masson-Delmotte, V. and Mestre, O.: Tree age, site and climate controls on tree ring cellulose δ18O: a case study on oak trees from south-western France, Dendrochronologia, 32, 78–89, doi:10.1016/j.dendro.2013.1011.1001, 2014.

Lamarre, A., Garneau, M. and Asnong, H.: Holocene palaeohydrological reconstruction and carbon accumulation of a permafrost peatland using testate amoeba and macrofossil analyses, Kuujjuarapik, subarctic Québec, Canada, Rev. Palaeobot. Palynol., 186, 131–141, doi:0.1016/j.revpalbo.2012.04.009, 2012.

Lamoureux, S., Gilbert, R.: A 750-yr record of autumn snowfall and temperature variability and winter storminess recorded in the varved sediments of Bear Lake, Devon Island, Arctic Canada, Quat. Res., 61, 134-147, doi:10.1016/j.yqres.2003.11.003, 2004.

Lamoureux, S., Stewart, K., Forbes, A., Fortin, D. Multidecadal variations and decline in spring discharge in the Canadian middle Arctic since 1550 AD, Geophys. Res. Lett., 33, L02403, doi10.1029/2005GL024942, 2006.

Lamoureux, S.: Five centuries of interannual sediment yield and rainfall-induced erosion in the Canadian High Arctic recorded in lacustrine varves, Water Resour. Res., 36, 309-318, doi:10.1029/1999WR900271, 2000.

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, Clim. Past, 13, 411-420, doi:10.5194/cp-13-411-2017 2017.

Larsen, D. J., Miller, G. H., Geirsdottir, A., 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, doi:10.1016/j.quascirev.2011.05.026, 2011.

Le Roux, G. and Marshall, W. A.: Constructing recent peat accumulation chronologies using atmospheric fall-out radionuclides, Mires and Peat, 7, Art. 8, (Online: http://www.mires-and-peat.net/pages/volumes/map07/map0708.php), 2011.

Lemke, P., Ren, J., Alley, R. B., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G., Mote, P., Thomas, R. H., Zhang, T.: Observations: changes in snow, ice and frozen ground. In: Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L. (Eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 337–383. 2007.

Lewis, D. and Smith. D.: Dendrochronological mass balance reconstruction, Strathcona Provincial Park, Vancouver Island, British Columbia, Canada, Arct. Antarct. Alp. Res., 36, 598–606, doi:10.1657/1523-0430(2004)036[0598:DMBRSP]2.0.CO;2, 2004.

Lewis, T., Braun, C., Hardy, D. R., Francus, P., Bradley R. S.: An Extreme Sediment Transfer Event in a Canadian High Arctic Stream, Arct. Antarct., Alp. Res., 37, 477-482, doi:10.1657/1523-0430(2005)037[0477:AESTEI]2.0.CO;2, 2005.

Lewis, T., Francus, P., Bradley R. S.: Recent occurrence of large jökulhlaups at Lake Tuborg, Ellesmere Island, Nunavut, J. Paleolimnol., 41, 491-506, doi:10.1007/s10933-008-9240-4, 2009.

Li, W. K. W., McLaughlin, F. A., Lovejoy, C. and Carmack, E.C.: Smallest Algae Thrive as the Arctic Ocean Freshens Science, 326, 539, doi:10.1126/science.1179798, 2009.

Linderholm, H. W. and Chen, D.: Central Scandinavian winter precipitation variability during the past five centuries reconstructed from Pinus sylvestris tree rings, Boreas, 34, 43–52, doi:10.1111/j.1502-3885.2005.tb01003.x, 2005.

Linderholm, H. W. and Jansson, P.: Proxy data reconstructions of the Storglaciären (Sweden) mass-balance record back to AD 1500 on annual to decadal timescales, Ann. Glaciol., 46, 261–267, doi:10.3189/172756407782871404, 2007.

Linderholm, H. W., Björklund, J. A., Seftigen, K., Gunnarson, B. E., Grudd, H., Drobyshev, I., Jeong, J.-H. and Liu Y.: Dendroclimatology in Fennoscandia – from past accomplishments to future potentials, Clim. Past, 6, 93-114, doi:10.5194/cp-6-93-2010, 2010.

Ljungqvist, F. C., Krusic, P.J., Sundqvist, H.S., Zorita, E., Brattström, G. and Frank, D.: Northern Hemisphere hydroclimatic variability over the past twelve centuries, Nature 532, 94–98, doi:10.1038/nature17418L3, 2016.

Ljungqvist, F. C.: A new reconstruction of temperature variability in the extra-tropical Northern Hemisphere during the last two millennia, Geogr. Ann., 92A, 339–351, doi:10.1111/j.1468-0459.2010.00399.x, 2010.

Loader, N. J., Young, G. H. F., Grudd, H. and McCarroll, D.: Stable carbon isotopes from Torneträsk, northern Sweden provide a millennial length reconstruction of summer sunshine and its relationship to Arctic circulation, Quat. Sci. Rev. 62, 97–113, doi:10.1016/j.quascirev.2012.11.014, 2013.

Loisel, J. and Garneau, M.: Late Holocene palaeoecohydrology and carbon accumulation estimates from two boreal peat bogs in eastern Canada: Potential and limits of multi-proxy archives, Palaeogeogr. Palaeoclimatol. Palaeoecol., 291, 493–533, doi. 10.1016/j.palaeo.2010.03.020, 2010.

Loisel, J., and Yu, Z.: Surface vegetation patterning controls carbon accumulation in peatlands, Geophys. Res. Lett., 40, 5508–5513, doi:10.1002/grl.50744, 2013.

Loisel, J., Garneau, M., Hélie, J.-F.: Modern Sphagnum δ13C signatures follow a surface moisture gradient in two boreal peat bogs, James Bay lowlands, Québec, J. Quat. Sci., 24, 209–214, doi:10.1002/jqs.1221, 2009.

Lubinski, D. J., Forman, S. L, Miller, G. H.: Holocene glacier and climate fluctuations on Franz Josef Land, Arctic Russia, 80° N, Quat. Sci. Rev., 18, 85–108, doi:10.1016/S0277-3791(97)00105-4, 1999.

Luckman, B. H.: Glacier fluctuations and tree-ring records for the last millennium in the Canadian Rockies, Quat. Sci. Rev., 12, 441–450, doi:10.1016/S0277-3791(05)80008-3, 1993.

Luoto T. P. and Helama, S.: Palaeoclimatological and palaeolimnological records from fossil midges and tree-rings: the role of the North Atlantic Oscillation in eastern Finland through the Mediaeval Climate Anomaly and Little Ice Age, Quat. Sci. Rev., 29, 2411–2423, doi:10.1016/j.quascirev.2010.06.015, 2010.

Luoto T. P., Helama S., and Nevalainen, L.: Stream flow intensity of the Saavanjoki River, eastern Finland, during the past 1500 years reflected by mayfly and caddisfly mandibles in adjacent lake sediments, J. Hydrol., 476, 147–153, doi:10.1016/j.jhydrol.2012.10.029, 2013.

Luoto, T. P. and Helama, S.: Palaeoclimatological and palaeolimnological records from fossil midges and tree-rings: the role of the North Atlantic Oscillation in eastern Finland through the Medieval Climate Anomaly and Little Ice Age, Quat. Sci. Rev., 29, 2411-2423, doi:10.1016/j.quascirev.2010.06.015, 2010.

Luoto, T. P., and Nevalainen, L.: Late Holocene precipitation and temperature changes in Northern Europe linked with North Atlantic forcing, Clim. Res., 66, 37–48, doi:10.3354/cr01331, 2015.

Luoto, T. P., and Nevalainen, L.: Quantifying climate changes of the Common Era for Finland, Clim. Dyn., doi:10.1007/s00382-016-3468-x, 2017.

Luoto, T. P.: A Finnish chironomid- and chaoborid-based inference model for reconstructing past lake levels, Quat. Sci. Rev., 28, 1481–1489, doi:0.1016/j.quascirev.2009.01.015, 2009.

Mann, D. H., Heiser, P. A. and Finney, B. P.: Holocene history of the Great Kobuk sand dunes, northwestern Alaska, Quat. Sci. Rev., 21, 709-731, doi:10.1016/S0277-3791(01)00120-2, 2002.

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

Masson-Delmotte, V., Hou, S., Ekaykin, A., Jouzel, J., Aristarain, A., Bernardo, R. T., Bromwich, D., Cattani, O., Delmotte, M., Falourd, S., Frezzotti, M., Gallée, H., Genoni, L., Isaksson, E., Landais, A., Helsen, M. M., Hoffmann, G., Lopez, J., Morgan, V., Motoyama, H., Noone, D., Oerter, H., Petit, J. R., Royer, A., Uemura, R., Schmidt, G. A., Schlosser, E., Simões, J. C., Steig, E. J., Stenni, B., Stievenard, M., van den Broeke, M. R., van de Wal, R. S. W., van de Berg, W. J., Vimeux, F. and White, J. W. C.: A Review of Antarctic Surface Snow Isotopic Composition: Observations, Atmospheric Circulation, and Isotopic Modeling, J. Clim., 21, 3359–3387, doi:10.1175/2007JCLI2139.1, 2008.

Mathijssen, P., Tuovinen, J-P., Lohila, A., Aurela, M., Juutinen, S., Laurila, T., Niemelä, E., Tuittila, E-S., Väliranta, M.: Development, carbon accumulation and radiative forcing of a subarctic fen over the Holocene. Holocene 24, 1156-1166. doi:10.1177/0959683614538072, 2014.

Mathijssen, P.J.H., Kähkölä, N., Tuovinen, J-P., Lohila, A., Minkkinen, K., Laurila, T. and Väliranta, M.: Lateral expansion and carbon exchange of a boreal peatland in Finland resulting in 7000 years of positive radiative forcing, J. Geophys. Res. Biogeosci., 122, 562–577, doi:10.1002/2016JG003749, 2017.

Mathijssen, P.J.H., Väliranta, M., Korrensalo, A., Alekseychik, P., Vesala, T., Rinne, J. and Tuittila, E-S.: Holocene carbon dynamics reconstruction from a large boreal peatland complex, southern Finland, Quat. Sci. Rev., 142, 1-15, doi:10.1016/j.quascirev.2016.04.013, 2016.

Matthews, J. A., Berrisford, M. S., Dresser, P. Q., Nesje, A., Dahl, S. O., Bjune, A. E., Bakke, J., Birks, H. J. B., Lie, Ø., Dumayne-Peaty, L. and Barnett, C.: Holocene glacier history of Bjørnbreen and climatic reconstruction in central Jotunheimen, Norway, based on proximal glaciofluvial stream-bank mires. Quat. Sci. Rev., 24, 67–90, doi:10.1016/j.quascirev.2004.07.003, 2005.

Mauquoy, D., Hughes, P. D. M., and van Geel, B.: A protocol for plant macrofossil analysis of peat deposits, Mires and Peat, 7, Article 6, (Online: http://www.mires-and-peat.net/pages/volumes/map07/map0706.php), 2010.

Mauquoy, D., van Geel, B., Blaauw, M. and van der Plicht, J.: Evidence from northwest European bogs shows “Little Ice Age” climatic changes driven by variations in solar activity, The Holocene 12, 1–6, doi:0.1191/0959683602hl514rr, 2002.

Mauquoy, D., van Geel, B., Blaauw, M., Speranza, A. and van der Plicht, J.: Changes in solar activity and Holocene climate shifts derived from ^{14}C wiggle-match dated peat deposits, Holocene, 14, 45–52, doi:10.1191/0959683604hl688rp, 2004.

Mauquoy, D., Yeloff, D., van Geel, B., Charman, D. J. and Blundell, A.: Two decadally resolved records from north-west European peat bogs show rapid climate changes associated with solar variability during the mid-late Holocene, J. Quat. Sci., 23, 745–763, doi:10.1002/jqs.1158, 2008.

McCarroll, D. and Loader, N. J.: Stable isotopes in tree rings, Quat. Sci. Rev., 23, 771–801, doi:10.1016/j.quascirev.2003.06.017, 2004.

McCarroll, D. and Pawellek, F.: Stable carbon isotope ratios of latewood cellulose in Pinus sylvestris from northern Finland: variability and signal strength, Holocene, 8, 693–702, doi:10.1191/095968398675987498, 1998.

McCarroll, D., Gagen, M. H., Loader, N. J., Robertson, I., Anchukaitis, K. J., Los, S., Young, G. H. F., Jalkanen, R., Kirchhefer, A. J. and Waterhouse, J. S.: Correction of tree ring stable carbon isotope chronologies for changes in the carbon dioxide content of the atmosphere. Geochim. Cosmochim. Acta. 73, 1539–154, doi:10.1016/j.gca.2008.11.041, 2009.

McCarroll, D., Jalkanen, R., Hicks, S., Tuovinen, M., Pawellek, F., Gagen, M., Eckstein, D., Schmitt, U., Autio, J. and Heikkinen, O.: Multi-proxy dendroclimatology: a pilot study in northern Finland, Holocene, 13, 829–838, doi:10.1191/0959683603hl668rp, 2003.

McCarroll, D., Loader, N. J., Jalkanen, R., Gagen, M., Grudd, H., Gunnarson, B. E., Kirchhefer, A. J., Friedrich, M., Linderholm, H. W., Lindholm, M., Boettger, T., Los, S. O., Remmele, S., Kononov, Y. M., Yamazaki, Y. H., Young, G. H. F., and Zorita, E.: A 1200-year multi-proxy record of tree growth and summer temperature at the northern pine forest limit of Europe, Holocene, 23, 471–484, doi:10.177/0959683612467483, 2013.

McCarroll, D., Pawellek, F.: Stable carbon isotope ratios of Pinus sylvestris from northern Finland and the potential for extracting a climate signal from long Fennoscandian chronologies, Holocene, 11, 517–526, doi:10.1191/095968301680223477, 2001.

McCarroll, D., Tuovinen, M., Campbell, R., Gagen, M., Grudd, H., Jalkanen, R., Loader, N. J. and Robertson, I.: A critical evaluation of multi-proxy dendroclimatology in northern Finland, J. Quat. Sci., 26, 7–14, doi:10.1002/jqs.1408, 2011.

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.

McKay, N. P., and Kaufman, D. S.: Holocene climate and glacier variability at Hallet and Greyling Lakes, Chugach Mountains, south-central Alaska. J. Paleolimnol., 41, 143–159, doi:10.1007/s10933-008-9260-0, 2009.

Medeiros, A. S. K., Gajewski, J., Vermaire, D., Porinchu, J. C. and Wolfe, B. B.: Detecting the influence of secondary environmental gradients on chironomid-inferred palaeotemperature reconstructions. Quat. Sci. Rev., 124, 265–274 doi: 10.1016/j.quascirev.2015.07.010, 2015.

Meese, D. A., Gow, A. J., Grootes, P., Mayewski, P. A., Ram, M., Stuiver, M., Taylor, K.C., Waddington, E.D. and Zielinski, G. A.: The accumulation record from the GISP2 core as an indicator of climate change throughout the Holocene, Science, 1680-1682, doi:10.1126/science.266.5191.1680, 1994.

Meko, D. M., Therrell, M. D., Baisan, C. H. and Hughes, M. K.: Sacramento River flow reconstructed to A.D. 869 from tree rings, J. Am. Water Resour. Assoc., 37, 1029–1039, doi:10.1111/j.1752-1688.2001.tb05530.x, 2001.

Menounos, B., Osborn, G., Clague, J. J., Luckman, B. H.: Latest Pleistocene and Holocene glacier fluctuations in western Canada, Quat. Sci. Rev., 28, 2049–2074, doi:10.1016/j.quascirev.2008.10.018, 2009.

Min, S. K., Zhang, X. and Zweirs, F.: Human-induced Arctic moistening, Science, 320, 518–520, doi:10.1126/science.1153468, 2008.

Mitchell, E. A. D., Charman, D. J. and Warner, B. G.: Testate amoebae analysis in ecological and palaeoecological studies of wetlands: past, present and future, Biodivers. Conserv., 17, 2115–2137, doi:10.1007/s10531-007-9221-3, 2008.

Moore, T. A. and Shearer, J. C.: Evidence for aerobic degradation of Palangka Raya peat and implications for its sustainability, In: Biodiversity and Sustainability of Tropical Peatlands, [Rieley, J.O. & Page, S.E. (eds.)], Samara Publishing, Cardigan, U.K. pp. 157–168, 1997.

Moossen, H., Bendle, J., Seki, O., Quillmann, U. and Kawamura, K.: North Atlantic Holocene climate evolution recorded by high-resolution terrestrial and marine biomarker records, Quat. Sci. Rev., 129, 111-127, doi:10.1016/j.quascirev.2015.10.013, 2015.

Moron, V., Robertson, A. W. and Ward, M. N. : Seasonal predictability and spatial coherence of rainfall characteristics in the tropical settings of Senegal, Mon. Wea. Rev., 134, 3248–3262, doi : 10.1175/MWR3252.1, 2006.

Mosley-Thompson, E., McConnell, J. R., Bales, R. C., Li, Z., Lin, P.-N., Steffen, K., Thompson, L. G., Edwards, R. and Bathke, D.: Local to regionalscale variability of annual net accumulation on the Greenland Ice Sheet from PARCA cores, J. Geophys. Res., 106, 33839–33851, doi:10.1029/2001JD900067, 2001.

Muschitiello, F., Pausata, F.S., Watson, J. E., Smittenberg, R. H., Salih, A. A., Brooks, S. J., Whitehouse, N. J., Karlatou-Charalampopoulou, A. and Wohlfarth, B.: Fennoscandian freshwater control on Greenland hydroclimate shifts at the onset of the Younger Dryas, Nature comm., 6, 8939, doi:10.1038/ncomms9939 , 2015.

Naulier, M., Savard, M. M., Bégin, C., Marion, J., Arseneault, D. and Bégin, Y.: Carbon and oxygen isotopes of lakeshore black spruce trees in northeastern Canada as proxies for climatic reconstruction, Chem. Geol., 37, 374–375, doi:10.1016/j.chemgeo.2014.02.031, 2014.

Nesje, A. and Dahl, S. O.: The ‘Little Ice Age’—only temperature? Holocene, 13, 139–145, doi:10.1191/0959683603hl603fa, 2003.

Nesje, A., Dahl, S. O., Thun, T. and Nordli, Ø.: The ‘Little Ice Age’ glacial expansion in western Scandinavia e summer temperature or winter precipitation? Clim. Dyn., 30, 789–801, doi:10.1007/s00382-007-0324-z, 2007.

Nesje, A.: Latest Pleistocene and Holocene alpine glacier fluctuations in Scandinavia, Quat. Sci. Rev., 28, 2119–2136, doi:10.1016/j.quascirev.2008.12.016, 2009.

Nevalainen, L., and Luoto, T. P.: Intralake training set of fossil Cladocera for palaeohydrological inferences: evidence for multicentennial drought during the Mediaeval Climate Anomaly, Ecohydrology, 5, 834–840, doi:10.1002/eco.275, 2012.

Nevalainen, L., Helama, S., and Luoto T. P.: Hydroclimatic variations over the last millennium in eastern Finland disentangled by fossil Cladocera, Palaeogeogr. Palaeoclimatol. Palaeoecol., 378, 13–21, doi:10.1016/j.palaeo.2013.03.016, 2013.

Nevalainen, L., Sarmaja-Korjonen, K., and Luoto, T. P.: Sedimentary Cladocera as indicators of past water-level changes in shallow northern lakes, Quat. Res., 75, 430–437, doi:10.1016/j.yqres.2011.02.007, 2011.

Nicault, A., Alleaume, S., Brewer, S., Carrer, M., Nola, P., Guttierez, E., Edouard, J. L., Urbinati, C. and Guiot, J.: Mediterranean Drought fluctuation during the last 500 years based on tree-ring data, Clim. Dyn., 31, 227–245, doi:10.1007/s00382-007-0349-3, 2007.

Nichols, J. E., Walcott, M., Bradley, R., Picher, J. and Youngsong, H.: Quantitative assessment of precipitation seasonality and summer surface wetness using ombrotrophic sediments from an Arctic Norwegian peatland, Quat. Res., 72, 443–451, doi:10.1016/j.yqres.2009.07.007, 2009.

Nilsson, M., Klarqvist, M., Bohlin, E. and Possnert, G.: Variation in radiocarbon age of macrofossils and different fractions of minute peat samples dates by AMS, Holocene, 11, 579–586, doi:10.1191/095968301680223521, 2001.

Nordli, Ø., Lie, Ø., Nesje, A. and Benestad, R. E.: Glacier mass balance in southern Norway modelled by circulation indices and spring–summer temperatures AD 1781–2000, Geogr. Ann., 87, 431–445, doi:10.1111/j.0435-3676.2005.00269.x, 2005.

Oerlemans, J.: Glaciers and climate change, 148 pp., A. A. Balkema Publishers, 2001

Oerlemans, J.: Quantifying global warming from the retreat of glaciers, Science, 264, 243-245, doi:10.1126/science.264.5156.243, 1994.

Ojala, A. E. K. and Alenius, T.: 10000 years of interannual sedimentation recorded in the Lake Nautajärvi (Finland) clastic–organic varves, Palaeogeogr. Palaeoclimatol. Palaeoecol., 219, 285-302, doi:10.1016/j.palaeo.2005.01.002, 2005.

Ojala, A. E. K. and Francus, P.: X-ray densitometry vs. BSE-image analysis of thin-sections: a comparative study of varved sedi- ments of Lake Nautajärvi, Finland, Boreas 31, 57–64, doi:10.1111/j.1502-3885.2002.tb01055.x, 2002.

Ojala, A. E. K., Kosonen, E., Weckström, J., Korkonen, S. and Korhola, A.: Seasonal formation of clastic-biogenic varves: the potential for palaeoenvironmental interpretations, GFF 135, 3-4: 237-247, doi:10.1080/11035897.2013.801925, 2013.

Ojala, A. E. K., Saarinen, T. & Salonen, V.-P.: Preconditions for the formation of annually laminated lake sediments in south- ern and central Finland, Bor. Env. Res., 5, 243– 255, 2000.

Ortega, P., Lehner, F., Swingedouw, D., Masson-Delmotte, V., Raible, C. C., Casado, M., and Yiou, P.: A model-tested North Atlantic Oscillation reconstruction for the past millennium, Nature, 523, 71–74, doi:10.1038/nature14518, 2015.

Outridge, P. M, Sanei, H., Courtney Mustaphi C. J. and Gajewski, K.: Holocene climate change influences on trace metal and organic matter geochemistry over 7000 years in a varved Arctic lake sediment profile, Appl. Geochem., 78, 35–48, doi:10.1016/j.apgeochem.2016.11.018, 2017.

Overland, J. E., Dethloff, K., Francis, J. A., Hall, R. J., Hanna, E., Kim, S-J., Screen, J. A., Shepherd, T. G. and Vihma, T.: Nonlinear response of mid-latitude weather to the changing Arctic, Nature Clim. Change, 6, 992–999, doi:10.1038/nclimate3121, 2016.

Overland, J. E.: Atmospheric Science: Long-range linkage, Nature Clim. Change, 4, 11–12, doi:10.1038/nclimate2079, 2014.

Overpeck, J. Hughen, K. Hardy, D. Bradley, R. Case, R. Douglas, M. Finney, B. Gajewski, K. Jacoby, G. Jennings, A. Lamoureux, S. Lasca, A. MacDonald, G. Moore, J. Retelle, M. Smith, S. Wolfe, A. and Zielinski. G.: Arctic environmental change of the last four centuries, Science, 278, 1251–1255, doi:10.1126/science.278.5341.1251, 1997.

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

Pancost, R., Baas, M., van Geel, B. and Sinninghe Damste, J. S.: Bioarkers as proxies for plant inputs to peats: an example from a sub-boreal ombrotrophic bog, Org. Geochem., 33, 675–690, doi:10.1016/S0146-6380(02)00048-7, 2002.

Parnell, A. C., Buck, C. E. and Doan, T. K.: A review of statistical chronology models for high-resolution, proxy-based Holocene palaeoenvironmental reconstruction, Quat. Sci. Rev., 30, 2948–2960, doi:10.1016/j.quascirev.2011.07.024, 2011.

Paterson, W. S. B. and Waddington E. D.: Past precipitation rates derived from ice core measurements: Methods and data analysis, Rev. Geophys., 22, 123–130, doi:10.1029/RG022i002p00123, 1984.

Payne, R. J., Kishaba, K., Blackford J. J. and Mitchell E. A. D.: Ecology of testate amoebae (Protista) in south-central Alaska peatlands: building transfer-function models for palaeoenvironmental studies, Holocene, 16, 403–414, doi:10.1191/0959683606hl936rp, 2006.

Payne, R. J.: Can testate amoeba-based palaeohydrology be extended to fens? J. Quat. Sci., 26, 15-27, doi:10.1002/jqs.1412, 2011.

Pedersen, R. A., Cvijanovic, I., Langen, P. L. and Vinther, B. M.: The Impact of Regional Arctic Sea Ice Loss on Atmospheric Circulation and the NAO, J. Clim., 29, 889–902, doi:10.1175/JCLI-D-15-0315.1, 2016.

Pederson, N., Jacoby, G. C., D'Arrigo, R., Buckley, B., Dugarjav, C. and Mijiddorj, R.: Hydrometeorological Reconstructions for Northeastern Mongolia Derived from Tree Rings: AD 1651-1995. J. Clim., 4, 872–881, doi:10.1175/1520-0442(2001)014<0872:HRFNMD>2.0.CO;2, 2001.

Peros, M. and Gajewski, K.: Holocene climate and vegetation change on Victoria Island, western Canadian Arctic, Quat. Sci. Rev., 27, 235–249, doi:10.1016/j.quascirev.2007.09.002, 2008.

Peros, M. and Gajewski, K.: Pollen-based reconstructions of late Holocene climate from the central and western Canadian Arctic, J. Paleolimnol., 41, 161–175, doi:10.1007/s10933-008-9256-9, 2009.

Peros, M., Gajewski, K., Paull, T., Ravindra, R. and Podritske, B.: Multi-proxy record of postglacial environmental change, south-central Melville Island, Northwest Territories, Canada, Quat. Res., 73, 247–258, doi:10.1016/j.yqres.2009.11.010, 2010.

Perren, B. B., Anderson, N. J., Douglas, M. S. and Fritz, S. C.: The influence of temperature, moisture, and eolian activity on Holocene lake development in West Greenland, J. Paleolimnol., 48, 223-239, doi:10.1007/s10933-012-9613-6, 2012.

Peterson, B. J., McClelland, J., Curry, R., Holmes, R. M., Walsh, J. E. and Aagaard, K.: Trajectory Shifts in the Arctic and Subarctic Freshwater Cycle, Science, 313, 1061–1066, doi:10.1126/science.1122593, 2006.

Petterson, G., Odgaard, B. V. and Renberg, I.: Image analysis as a method to quantify sediment components, J. Paleolimnol., 22, 443-455, doi:10.1023/A:1008070811190, 1999.

Pierrehumbert, R.T.: Huascaran δ18O as an indicator of tropical climate during the Last Glacial Maximum, Geophys. Res. Lett., 26, 1345-1348, doi:10.1029/1999GL900183, 1999.

Pisaric, M. F. J., St-Onge, S. M. and Kokelj, S. V.: Tree-ring reconstruction of early-growing season precipitation from Yellowknife, Northwest Territories, Canada, Arctic, Arct. Antarc. Alp. Res., 41, 486–496, doi:10.1657/1938-4246-41.4.486, 2009.

Poli, P., Hersbach, H. Tan, D. Dee, D. Thépaut, J.-N. Simmons, A. Peubey, C. Laloyaux, P. Komori, T. Berrisford, P. Dragani, R. Trémolet, Y. Hólm, E. Bonavita, M. Isaksen L. and Fisher M.: The data assimilation system and initial performance evaluation of the ECMWF pilot reanalysis of the 20th-century assimilating surface observations only (ERA-20C), ERA Report Series no 14, ECMWF Technical Report, U. K., 2013.

Polissar, P.J. and Freeman, K.H.: Effects of aridity and vegetation on plant-wax δD in modern lake sediments, Geochim. Cosmochim. Acta, 74, 5785-5797, doi:10.1016/j.gca.2010.06.018, 2010.

Polyak, L., Murdmaa, I. and Ivanova, E.: A high-resolution, 800-year glaciomarine record from Russkaya Gavan', a Novaya Zemlya fjord, eastern Barents Sea, Holocene, 14, 628–634, doi:10.1191/0959683604hl740rr, 2004.

Porter, T. J., Pisaric, M. F. J., Field, R. D., Kokelj, S. V., Edwards, T. W. D., deMontigny, P., Healy, R. and LeGrande, A. N.: Spring-summer temperatures since AD 1780 reconstructed from stable oxygen isotope ratios in white spruce tree-rings from the Mackenzie Delta, northwestern Canada, Clim. Dyn., 42, 771–785, doi:10.1007/s00382-013-1674-3, 2014.

Porter, T. J., Pisaric, M. F. J., Kokelj, S. V. and Edwards, T. D. W.: Climatic Signals in $\delta^{13}C$ and $\delta^{18}O$ of Tree-rings from White Spruce in the Mackenzie Delta Region, Northern Canada, Arct., Antarc., Alp. Res., 41, 497–505, doi:10.1657/1938-4246-41.4.497, 2009.

Rach, O., Brauer, A., Wilkes, H. and Sachse, D.: Delayed hydrological response to Greenland cooling at the onset of the Younger Dryas in western Europe, Nature Geosci., 7, 109-112, doi:10.1038/ngeo2053, 2014.

Rach, O., Kahmen, A., Brauer, A., and Sachse, D.: A dual-biomarker approach for quantification of changes in relative humidity from sedimentary lipid D / H ratios, Clim. Past Discuss., doi:10.5194/cp-2017-7, 2017.

Rahmstorf, S.: Bifurcations of the Atlantic Thermohaline Circulation in Response to Changes in the Hydrological Cycle, Nature, 378, 146–149, doi:10.1038/378145a0, 1995.

Rasmussen, L. A., Andreassen, L. M., Baumann, S. and Conway, H.: Little Ice Age precipitation in Jotunheimen, southern Norway, Holocene, 20, 1039–1045, doi:10.1177/0959683610369510, 2010.

Reusche, M., Winsor, K., Carlson, A. E., Marcott, S. A., Rood, D. H., Novak, A., Roof, S., Retelle, M., Werner, A., Caffee, M. and Clark, P. U.: 10Be surface exposure ages on the late-Pleistocene and Holocene history of Linnebreen on Svalbard, Quat. Sci. Rev., 89, 5–12, doi:10.1016/j.quascirev.2014.01.017, 2014.

Rhein, M., Rintoul, S.R. Aoki, S. Campos, E. Chambers, D. Feely, R.A. Gulev, S. Johnson, G.C. Josey, S.A. Kostianoy, A. Mauritzen, C. Roemmich, D. Talley L.D. and Wang, F.: Observations: Ocean, In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Rice, S. K.: Variation in carbon isotope discrimination within and among Sphagnum species in a temperate wetland, Oecologia, 123, 1–8, doi:10.1007/s004420050983, 2000.

Rinne, K. T., Saurer M., Kirdyanov, A.V., Loader, N. J., Bryukhanova, M. V., Werner, R. A. and Siegwolf, R. T. W.: The relationship between needle sugar carbon isotope ratios and tree rings of larch in Siberia, Tree Physiol., 35, 1192-1205, doi:10.1093/treephys/tpv096, 2015.

Roden, J. S., Lin, G. and Ehleringer, J. R.: A mechanistic model for inter-pretation of hydrogen and oxygen isotope ratios in tree-ring cellulose, Geochim. Cosmochim. Acta, 64, 21–35, doi:10.1016/S0016-7037(99)00195-7, 2000.

Røthe, T. O., Bakke, J., Vasskog, K., Gjerde, M., D'Andreas, W. J. and Bradley, R. S.: Artic Holocene glacier fluctuations reconstructed from lake sediments at Mitrahalvøya, Spitsbergen, Quat. Sci. Rev., 109, 111–125, doi:org/10.1016/j.quascirev.2014.11.017, 2015.

Rowell, D. P. :: Assessing potential seasonal predictability with an ensemble of multidecedal GCM simulations, J. Clim., 11, 109–120, doi: 10.1175/1520-0442(1998)011<0109:APSPWA>2.0.CO;2, 1998.

Rozanski, K. Johnsen, S. J. Schotterer, U. and Thompson, L. G.: Reconstruction of past climates from stable isotope records of palaeo-precipitation preserved in continental archives, Hydrol. Sci. J., 42, 725–745, doi:10.1080/02626669709492069, 1997.

Ruppel, M., Väliranta, M., Virtanen, T. and Korhola, A.: Postglacial spatiotemporal peatland initiation and lateral expansion dynamics in Europe and North-America. Holocene, 23, 1596–1606, doi:10.1177/0959683613499053, 2013.

Rydberg, J. and Martinez-Cortizas, A.: Geochemical assessment of an annually laminated lake sediment record from northern Sweden: a multi-core, multi-element approach, J. Paleolimnol., 51, 499-514, doi:10.1007/s10933-014-9770-x, 2014.

Rydin, H. and Jeglum, J.: The Biology of Peatlands. Oxford University Press, Rochester USA, 2006.

Saarni, S., Saarinen, T., and Dulski, P.: Between the North Atlantic Oscillation and the Siberian High: A 4000-year snow accumulation history inferred from varved lake sediments in Finland, Holocene, 26, 423–431, doi:10.1177/0959683615609747, 2016.

Saarni, S., Saarinen, T., and Lensu, A.: Organic lacustrine sediment varves as indicators of past precipitation changes: a 3,000-year climate record from Central Finland, J. Palaeolimnol., 53, 401–413, doi:10.1007/s10933-015-9832-8, 2015.

Sachse, D., Billault, I., Bowen, G.J., Chikaraishi, Y., Dawson, T. E., Feakins, S. J., Freeman, K. H., Magill, C. R., McInerney, F. A., Meer, M. T. J. van der, Polissar, P., Robins, R. J., Sachs, J. P., Schmidt, H.-L., Sessions, A. L., White, J. W. C., West, J. B. and Kahmen, A.: Molecular Paleohydrology: Interpreting the Hydrogen-Isotopic Composition of Lipid Biomarkers from Photosynthesizing Organisms, Annu. Rev. Earth Planet. Sci., 40, 221–249, doi:10.1146/annurev-earth-042711-105535, 2012.

Sachse, D., Radke, J. and Gleixner, G.: Hydrogen isotope ratios of recent lacustrine sedimentary n-alkanes record modern climate variability. Geochim. Cosmochim. Acta, 68, 4877-4889, doi:10.1016/j.gca.2004.06.004, 2004.

Sauer, P. E., Eglinton, T. I., Hayes, J. M., Schimmelmann, A. and Sessions, A. L.: Compound-specific D/H ratios of lipid biomarkers from sediments as a proxy for environmental and climatic conditions, Geochim. Cosmochim. Acta, 65, 213–222, doi:10.1016/S0016-7037(00)00520-2, 2001.

Saurer, M., Kress, A., Leuenberger, M., Rinne, K. T., Treydte, K. S. and Siegwolf, R. T. W.: Influence of atmospheric circulation patterns on the oxygen isotope ratio of tree rings in the Alpine region, J Geophys. Res., 117, D05118. doi:10.01029/02011JD016861, 2012.

Saurer, M., Schweingruber, F. H., Vaganov, E. A., Shiyatov, S. G. and Siegwolf, R.: Spatial and temporal oxygen isotope trends at northern tree-line Eurasia, Geophys. Res. Lett., 29, 10–14, doi: 10.1029/2001GL013739, 2002.

Saurer, M., Siegwolf, R. T. W. and Schweingruber, F. H.: Carbon isotope discrimination indicates improving water-use efficiency of trees in northern Eurasia over the last 100 years, Glob. Change Biol., 10, 2109–2120, doi:10.1111/j.1365-2486.2004.00869.x, 2004.

Saurer, M., Spahni, R., Frank, D. C., Joos, F., Leuenberger, M., Loader, N. J., McCarroll, D., Gagen, M., Poulter, B., Siegwolf, R. T., Andreu-Hayles, L., Boettger, T., Dorado Liñán, I., Fairchild, I. J., Friedrich, M., Gutierrez, E., Haupt, M., Hilasvuori, E., Heinrich, I., Helle, G., Grudd, H., Jalkanen, R., Levanič, T., Linderholm, H. W., Robertson, I., Sonninen, E., Treydte, K., Waterhouse, J. S., Woodley, E. J., Wynn, P. M. and Young, G. H.: Spatial variability and temporal trends in water-use efficiency of European forests, Glob. Change Biol., 20, 3700–3712, doi:10.1111/gcb.12717, 2014.

Scheidegger, Y., Saurer, M., Bahn, M. and Siegwolf, R.: Linking stable oxygen and carbon isotopes with stomatal conductance and photosynthetic capacity: a conceptual model, Oecologia, 125, 350–357, doi:10.1007/s004420000466, 2000.

Schmidt, G. A., Jungclaus, J. H., Ammann, C. M., Bard, E., Braconnot, P., Crowley, T. J., Delaygue, G., Joos, F., Krivova, N. A., Muscheler, R., Otto-Bliesner, B. L., Pongratz, J., Shindell, D. T., Solanki, S. K., Steinhilber, F., and Vieira, L. E. A.: Climate forcing reconstructions for use in PMIP simulations of the last millennium (v1.0), Geosci. Model Dev., 5, 185–191, doi:10.5194/gmd-5-185-2012, 2012

Schneider, L., Smerdon, J. E., Büntgen, U., Wilson, R. J. S., Myglan, V. S., Kirdyanov, A. V., and Esper, J.: Revising midlatitude summer temperatures back to A.D. 600 based on a wood density network, Geophys. Res. Lett., 42, 4556–4562, doi:10.1002/2015gl063956, 2015.

Schubert, B. A. and Jahren, A. H.: Seasonal temperature and precipitation recorded in the intra-annaul oxygen isotope pattern of meteoric water and tree ring cellulose, Qaut. Sci. Rev., 125, 1–14, doi:10.1016/j.quascirev.2015.07.024, 2015.

Schurer, A. P., Hegerl, G. C., Mann, M. E., Tett, S. F. B., and Phipps, S. J.: Separating forced from chaotic climate variability over the Past Millennium, J. Climate, 26, 6954–6973, doi:10.1175/JCLI-D-12-00826.1, 2013.

Screen, J. A. and Francis, J. A.: Contribution of sea-ice loss to Arctic amplification regulated by Pacific Ocean decadal variability, Nature Clim. Change, 1758-6798, doi:10.1038/nclimate3011, 2016.

Screen, J.A. and Simmonds, I.: Declining snowfall in the Arctic: causes, impacts and feedbacks, Clim. Dyn., 38, 2243–2256, doi:10.1007/s00382-011-1105-2, 2012.

Seager, R., Graham, N., Herweijer, C., Gordon, A. L., Kushnir, Y. and Cook, E. R.: Blueprints for medieval hydroclimate. Quat. Sci. Rev., 26, 2322–2336, doi: 10.1016/j.quascirev.2007.04.020, 2007.

Seftigen, K., Björklund, J., Cook, E. R. and Linderholm, H. W.: A tree-ring field reconstruction of Fennoscandian summer hydroclimate variability for the last millennium, Clim. Dyn., 44, 3141–3154, doi:10.1007/s00382-014-2191-8, 2015b.

Seftigen, K., Cook, E. R., Linderholm, H. W., Fuentes, M. and Björklund, J.: The potential of deriving tree-ring based field reconstructions of droughts and pluvials over Fennoscandia, J. Clim., 28, 3453–3471, doi:10.1175/JCLI-D-13-00734.1, 2015a.

Seierstad, J., Nesje, A., Dahl, S.O. and Simonsen, J.: Holocene glacier fluctuations of Grovabreen and Holocene snow-avalanche activity reconstructed from lake sediments in Grøningstølsvatnet, western Norway, Holocene, 12, 211–222, doi:10.1191/0959683606hl954rp, 2002.

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

Serreze, M. C., Barrett, A. P., Stroeve1, J. C., Kindig, D. N. and Holland. M. M.: The emergence of surface-based Arctic amplification, Cryosphere, 3, 11–19, doi:10.5194/tc-3-11-2009, 2009.

Serreze, M. C., Walsh, J. E., Chapin, F. S., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W. C., Morison J., Zhang, T. and Barry, R. G.: Observational evidence of recent change in the northern high-latitude environment. Clim. Chang., 46, 159–207, doi:10.1023/A:1005504031923, 2000.

Shanahan, T. M., Hughen, K. A., Ampel, L., Sauer, P. E. and Fornace, K.: Environmental controls on the $^{2}H/^{1}H$ values of terrestrial leaf waxes in the eastern Canadian Arctic, Geochim. Cosmochim. Acta, 119, 286–301, doi:10.1016/j.gca.2013.05.032, 2013.

Shi, F., Yang, B., Ljungqvist, F. C., and Yang, F.: Multi-proxy reconstruction of Arctic summer temperatures over the past 1400 years, Clim. Res., 54, 113–128, doi:10.3354/cr01112, 2012.

Shi, X., Déry, S.J., Groisman, P.Y. and Lettenmaier, D. P.: Relationships between recent pan-Arctic snow cover and hydroclimate trends, J. Clim., 26, 2048–2064, doi:10.1175/JCLI-D-12-00044.1, 2013.

Sidorova, O. V., Siegwolf, R. T. W., Saurer, M., Naurzbaev, M. M. and Vaganov, E. A.: Isotopic composition (δ13C, δ18O) in wood and cellulose of Siberian larch trees for early Mediaeval and recent periods, J. Geophys. Res., 113, G02019, doi:10.1029/2007JG000473, 2008.

Sidorova, O. V., Siegwolf, R. T. W., Saurer, M., Shashkin, A. V., Knorre, A. A., Prokushkin, A. S., Vaganov, E. A. and Kirdyanov, A. V.: Do centennial tree-ring and stable isotope trends of Larix gmelinii (Rupr.) Rupr. indicate increasing water shortage in the Siberian north? Oecologia, 161, 825–835, doi:10.1007/s00442-009-1411-0, 2009.

Sillasoo, Ü, Mauquoy, D., Blundell, A., Charman, D., Blaauw, M., Daniell, J. G. R., Toms, P., Newberry, J., Chambers, F. M. and Karofeld, E.: Peat multi-proxy data from Männikjärve bog as indicators of Late Holocene climate changes in Estonia, Boreas, 36, 20–37, doi:10.1111/j.1502-3885.2007.tb01177.x, 2007.

Sjolte, J., Hoffman, G., Johnsen, S. J., 2014. Modelling the response of stable water isotopes in Greenland precipitation to orbital configurations of the previous interglacial, Tellus B, 66, doi:10.3402/tellusb.v66.22872, 2014.

Slater, A. G., Bohn, T. J., McCreight, J. L., Serreze, M. C. and Lettenmaier D. P.: A multimodel simulation of pan-Arctic hydrology, J. Geophys. Res., 112, G04S45, doi:10.1029/2006JG000303, 2007.

Smerdon, J. E., Luterbacher, J., Phipps, S. J., Anchukaitis, K. J., Ault, T., Coats, S., Cobb, K. M., Cook, B. I., Colose, C., Felis, T., Gallant, A., Jungclaus, J. H., Konecky, B., LeGrande, A., Lewis, S., Lopatka, A. S., Man, W., Mankin, J. S., Maxwell, J. T., Otto-Bliesner, B. L., Partin, J. W., Singh, D., Steiger, N. J., Stevenson, S., Tierney, J. E., Zanchettin, D., Zhang, H., Atwood, A. R., Andreu-Hayles, L., Baek, S. H., Buckley, B., Cook, E. R., D'Arrigo, R., Dee, S. G., Griffiths, M., Kulkarni, C., Kushnir, Y., Lehner, F., Leland, C., Linderholm, H. W., Okazaki, A., Palmer, J., Piovano, E., Raible, C. C., Rao, M. P., Scheff, J., Schmidt, G. A., Seager, R., Widmann, M., Williams, A. P., and Xoplaki, E.: Comparing proxy and model estimates of hydroclimate variability and change over the Common Era, Clim. Past, 13, 1-49, 10.5194/cp-13-1-2017, 2017.

Snowball, I., Zillen, L. and Gaillard, M.J.: Rapid early-Holocene environmental changes in northern Sweden based on studies of two varved lake-sediment sequences, Holocene, 12, 7 – 16, doi:10.1191/0959683602hl515rp, 2002.

Soden, B. J. and Held, I. M.: An assessment of climate feedbacks in coupled ocean-atmosphere models, J Clim., 19, 3354–3360, doi:10.1175/JCLI3799.1, 2006.

Solomina, O. N., Bradley, R. S., Jomelli, V., Geirsdottir, A., Kaufman, D. S., Koch, J., McKay, N. P., Masiokas, M., Miller, G., Nesje, A., Nicolussi, K., Owen, L. A., Putnam, A. E., Wanner, H., Wiles, G. and Yang, B.: Glacier fluctuations during the past 2000 years, Quat. Sci. Rev., 149, 61–90, doi:10.1016/j.quascirev.2016.04.008, 2016.

Solomina, O., Bradley, R. S., Hodgson, D. A., Ivy-Ochs, S., Jomelli, V., Mackintosh, A. N., Nesje, A., Owen, L. A., Wanner, H., Wiles, G. C. and Young, N. E.: Holocene glacier fluctuations, Quat. Sci. Rev., 111, 9–34, doi:10.1016/j.quascirev.2014.11.018, 2015.

Sonninen, E. and Jungner, H. 1995: Stable carbon isotopes in tree-ringsof a Scots pine from northern Finland, In: Problems of stable isotopes in tree rings, lake sediments and peat bogs as climatic evidence for the Holocene [Frenzel, B., Stauffer, B. and Weiss, M., (eds),] Paläoklimaforschung, 15, 121–128.

St. George, S. and Ault, T. R.: The imprint of climate within Northern Hemisphere trees, Quat. Sci. Rev., 89, 1–4, doi:10.1016/j.quascirev.2014.01.007, 2014.

St. George, S.: An overview of tree-ring width records across the Northern Hemisphere, Quat. Sci. Rev., 95: 132–150, doi:10.1016/j.quascirev.2014.04.029, 2014.

Stahle, D. W. and Cleaveland, M. K.: Texas drought history reconstructed and analyzed from 1698 to 1980, J Clim., 1, 59–74, doi:10.1175/1520-0442(1988)001<0059:TDHRAA>2.0.CO;2, 1988.

Stien, A., Ims, R. A., Alborn, S. D., Fuglei, E., Irvine, R. J., Ropstad, E., Halvorsen, O., Langvatn, R., Loe, L. E., Veiberg, V. and Yoccoz, N. G.: Congruent responses to weather variability in high arctic herbivores, Biol. Lett., doi:10.1098/rsbl.2012.0764, 2012.

Stocker, T. F., Qin, D. Plattner, G.-K. Alexander, L. V., Allen, S. K., Bindoff, N. L., Bréon, F.-M., Church, J. A., Cubasch, U. Emori, S., Forster, P., Friedlingstein, P., Gillett, N., Gregory, J. M., Hartmann, D. L., Jansen, E., Kirtman, B., Knutti, R., Krishna Kumar, K., Lemke, P., Marotzke, J., Masson-Delmotte, V., Meehl, G. A., Mokhov, I. I., Piao, S., Ramaswamy, V., Randall, D., Rhein, M., Rojas, M., Sabine, C., Shindell, D., Talley, L. D., Vaughan, D. G. and Xie, S.-P.: Technical summary. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Doschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P. M. (eds)]. Cambridge University Press, 33–115, doi 10.1017/CBO9781107415324.005, 2013.

Stoffel, M., Khodri, M., Corona, C., Guillet, S., Poulain, V., Bekki, S., Guiot, J., Luckman, B. H., Oppenheimer, C., and Lebas, N.: Estimates of volcanic-induced cooling in the Northern Hemisphere over the past 1,500 years, Nat. Geosci., 8, 784–788, doi:10.1038/ngeo2526, 2015.

Stroeve, J. C., Serreze, M., Holland, M., Kay, J., Maslanik, J. and Barrett, A.: The Arctic’s rapidly shrinking sea ice cover: a research synthesis, Clim. Change, 110, 1005–10027, doi:10.1007/s10584-011-0101-1, 2012.

Sundqvist, H. S., Kaufman, D. S., McKay, N. P., Balascio, N. L., Briner, J. P., Cwynar, L. C., Sejrup, H. P., Seppä, H., Subetto, D. A., Andrews, J. T., Axford, Y., Bakke, J., Birks, H. J. B., Brooks, S. J., de Vernal, A., Jennings, A. E., Ljungqvist, F. C., Rühland, K. M., Saenger, C., Smol, J. P., and Viau, A. E.: Arctic Holocene proxy climate database – new approaches to assessing geochronological accuracy and encoding climate variables, Clim. Past, 10, 1605-1631, doi:10.5194/cp-10-1605-2014, 2014.

Svendsen, J. I. and Mangerud, J.: Holocene glacial and climatic variations on Svalbard, Svalbard, Holocene, 7, 45-57, doi:10.1177/095968369700700105, 1997.

Swindles, G. T., Amesbury, M. J, Turner, T. E., Carrivick, J. L., Woulds, C., Raby, C., Mullan, D., Roland, T. P., Galloway, J. M., Parry, L., Kokfelt, U., Garneau, M., Charman, D. J.and Holden, J.: Evaluating the use of testate amoebae for palaeohydrological reconstruction in permafrost peatlands, Palaeogeogr. Palaeoclimatol. Palaeoecol., 424, 111–122, doi:10.1016/j.palaeo.2015.02.004, 2015.

Swindles, G. T., Morris, P. J. Baird, A. J. Blaauw, M. and Plunkett, G.: Ecohy- drological feedbacks confound peat-based climate reconstructions, Geophys. Res. Lett., 39, L11401, doi:10.1029/2012GL051500, 2012.

Swindles, G. T., Plunkett, G. and Roe, H.: A delayed climatic response to solar forcing at 2800 cal. BP: multi-proxy evidence from three Irish peatlands, Holocene, 17, 177-182, doi:10.1177/0959683607075830, 2007.

Swindles, G.T., De Vleeschouwer, F. and Plunkett, G.: Dating peat profiles using tephra: stratigraphy, geochemistry and chronology, Mires and Peat, 7, Art. 5, (Online: http://www.mires-and-peat.net/pages/volumes/map07/map0705.php), 2010.

Tallis, J. H.: Changes in wetland communities, In: Ecosystems of the world 4A. Mires: swamp, bog, fen and moor. General studies [Gore, A.J.P. (ed.)], Elsevier Scientific Publishing Company, Amsterdam - Oxford - New York. pp. 311–347, 1983.

Taylor, K. E., Stouffer, R. J. and Meehl G. A.: An Overview of CMIP5 and the experiment design, Bull. Amer. Meteor. Soc., 93, 485–498, doi:10.1175/BAMS-D-11-00094.1, 2012.

Theakstone, W. H.: A seven-year study of oxygen isotopes in daily precipitation at a site close to the arctic circle, tustervatn, norway: Trajectory analysis and links with the north atlantic oscillation, Atm. Environ., 45, 5101-5109, doi: , 2011.

Thomas, E. K., Briner, J. P., Ryan-Henry, J. J. and Huang, Y.: 2016. A major increase in winter snowfall during the middle Holocene on western Greenland caused by reduced sea ice in Baffin Bay and the Labrador Sea, Geophys. Res. Lett., 43, 5302-5308, doi:10.1002/2016GL068513, 2016.

Thomas, E. K., McGrane, S., Briner, J. P. and Huang, Y.: Leaf wax δ2H and varve-thickness climate proxies from proglacial lake sediments, Baffin Island, Arctic Canada, J. Paleolimn., 48, 193-207, doi:10.1016/j.atmosenv.2011.06.034, 2012.

Thompson, L. G., Mosely-Thompson, E., Bolzan, J. F. and Koci, B. R.: A 1500-year record of tropical precipitation in ice cores from the Quelccaya Ice Cap, Peru, Science, 229, 971–973, doi:10.1126/science.229.4717.971, 1985.

Thompson, L. G., Yao, T., Mosely-Thompson, E., Davis, M. E., Henderson, K.A. and Lin, P.-N.: A high-resolution millennial record of the South Asian Monsoon from Himalayan ice cores, Science, 289, 1916–1919, doi:10.1126/science.289.5486.1916, 2000.

Tiljander, M., Saarnisto, M, Ojala, A. K. and Saarinen, T.: A 3000-year palaeoenvironmental record from annually laminated sediment of Lake Korttajarvi, central Finland, Boreas 32, 566-577, doi:10.1111/j.1502-3885.2003.tb01236.x, 2003.

Tomkins, J. D., Lamoureux, S. F, Antoniades, D. and Vincent, W. F.: Autumn snowfall and hydroclimatic variability during the past millennium inferred from the varved sediments of meromictic Lake A, northern Ellesmere Island, Canada, Quat. Res., 74, 188-198, doi:10.1016/j.yqres.2010.06.005, 2010.

Torbenson, M. C. A., Plunkett, G., Brown, D. M., Pilcher, J. R., and Leuschner, H. H.: Asynchrony in key Holocene chronologies: Evidence from Irish bog pines, Geology, 43, 799–802, doi:10.1130/G36914.1, 2015.

Torrence, C. and Compo, G. P.: A practical guide to wavelet analysis, Bull. Am. Meteorol. Soc., 79, 61–78, doi:10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2, 1998.

Touchan, R., Anchukaitis, K. J., Meko, D. M., Sabir, M., Attalah, S. and Aloui, A.: Spatiotemporal drought variability in northwestern Africa over the last nine centuries, Clim. Dyn., 37, 237–253, doi:10.1007/s00382-010-0804-4, 2011.

Treydte, K., Boda, S., Graf Pannatier, E., Fonti, P., Frank, D., Ullrich, B., Saurer, M., Siegwolf, R., Battipaglia, G., Werner, W. and Gessler, A.: Seasonal transfer of oxygen isotopes from precipitation and soil to the tree ring: source water versus needle water enrichment, New Phytol., 202, 772–783, doi:10.1111/nph.12741, 2014.

Treydte, K., Frank, D., Esper J., Andreu, L., Bednarz, Z., Berninger, F., Boettger, T. D., Alessandro, C. M., Etien, N., Filot, M., Grabner, M., Guillemin, M. T., Gutiérrez, E., Haupt, M., Helle, G., Hilasvuori, E., Jungner, H., Kalela-Brundin, M., Krapiec, M., Leuenberger, M., Loader, N. J., Masson-Delmotte, V., Pazdur, A., Pawelczyk, S., Pierre, M., Planells, O., Pukiene, R., Reynolds-Henne, C. E., Rinne, K. T., Saracino, A., Saurer, M., Sonninen, E., Stievenard, M., Switsur, V. R., Szczepanek, M., Szychowska-Krapiec, E., Todaro, L., Waterhouse, J. S., Weigl, M. and Schleser G. H.: Signal strength and climate calibration of a European tree-ring isotope network, Geophys. Res. Lett., 34, L24302, doi:10.1029/2007GL031106, 2007.

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

Tuittila, E.-S., Juutinen, S., Frolking, S., Väliranta, M., Laine, A. M., Miettinen, A., Seväkivi, M. –L., Quillet, A. and Merilä, P.: Wetland chronosequence as a model of peatland development: Vegetation succession, peat and carbon accumulation, Holocene, 23, 25–35, doi:10.1177/0959683612450197, 2013.

Tuittila, E-S., Väliranta, M., Laine, J., and Korhola, A.: Quantifying patterns and controls of mire vegetation succession in a southern boreal bog in Finland using partial ordinations, J. Veg. Sci., 18, 891-902, doi:10.1111/j.1654-1103.2007.tb02605.x, 2007.

Vaganov, E. A., Hughes, M. K. and Shashkin, A. V.: Growth dynamics of tree rings: an image of past and future environments, Springer-Verlag, Berlin, 368 pp, 2006.

Väliranta, M., Blundell, A., Charman, D., Karofeld, E., Korhola, A., Sillasoo, Ü. and Tuittila, E.: Reconstructing peatland water table using transfer function for plant macrofossils and testate amoebae: a methodological comparison. Quat. Int., 268, 34-43, doi:10.1016/j.quaint.2011.05.024, 2011.

Väliranta, M., Korhola, A., Seppä, H., Tuittila, E. S., Sarmaja-Korjonen, K., Laine, J. and Alm, J.: High-resolution reconstruction of wetness dynamics in a southern boreal raised bog, Finland, during the late Holocene: a quantitative approach, Holocene, 17, 1093-1107, doi:10.1177/0959683607082550, 2007.

Väliranta, M., Korhola, A., Seppä, H., Tuittila, E.-S., Sarmaja-Korjonen, K., Laine, J., and Alm, J.: High-resolution reconstruction of wetness dynamics in a southern boreal raised bog, Finland, during the late Holocene: a quantitative approach, Holocene, 17, 1093–1107, doi:10.1177/0959683607082550, 2007.

Väliranta, M., Oinonen, M., Seppä, H., Korkonen, S. & Tuittila, E-S.: Unexpected problems in AMS 14C dating of fen peat, Radiocarbon, 56, 95-108, doi:10.2458/56.16917, 2014.

Väliranta, M., Salojärvi, N., Vuorsalo, A., Juutinen, S., Korhola, A., Luoto, M. and Tuittila, E-S.: Holocene fen-bog transitions, current status in Finland and future perspectives, Holocene, 27, 752-764, doi:10.1177/0959683616670471, 2016.

Van Bellen, S, Dallaire, P.-L., Garneau, M. and Bergeron Y.: Quantifying spatial and temporal Holocene carbon accumulation in ombrotrophic peatlands of the Eastmain region, Quebec, Canada., Glob. Biogeochem. Cycles, 25, GB2016, doi:10.1029/2010GB003877, 2011.

van der Schrier G, Briffa, K. R., Osborn, T. J. and Cook, E. R.: Summer moisture availability across North America, J. Geoph. Res., 111, D11102, doi:10.1029/2005JD006745, 2006b.

van der Schrier G., Briffa, K. R., Jones, P. D. and Osborn, T. J.: Summer moisture variability across Europe, J. Clim., 19, 2818–2834, doi:10.1175/JCLI3734.1, 2006a.

Vasskog, K., Paasche, Ø., Nesje, A., Boyle, J. F. and Birks, H. J. B. : A new approach for reconstructing glacier variability based on lake sediments recording input from more than one glacier, Quat. Res., 77, 192-204, doi:10.1016/j.yqres.2011.10.001, 2012.

Vellinga, M. and Wood, R. A.: Global Climatic Impacts of a Collapse of the Atlantic Thermohaline Circulation, Clim. Change, 54: 251–267, doi:10.1023/A:1016168827653, 2002.

Viau, A. and Gajewski, K.: Reconstructing millennial-scale, regional palaeoclimates of boreal Canada during the Holocene, J. Clim., 22, 316–330, doi:10.1175/2008JCLI2342.1, 2009.

Viau, A., Gajewski, K., Sawada, M. and Bunbury, J.: Low- and High-frequency climate variability in eastern Beringia during the past 25 000 years, Can. J. Earth Sci., 45, 1435–1453, doi:10.1139/E08-036, 2008.

Vorren, K. D., Blaauw, M., Wastegård, S., Plicht, J. V. D. and Jensen, C.: High-resolution stratigraphy of the northernmost concentric raised bog in Europe: Sellevollmyra, Andøya, northern Norway, Boreas, 36, 253-277, doi:10.1111/j.1502-3885.2007.tb01249.x, 2007.

Vorren, K. D., Jensen, C. E. and Nilssen, E.: Climate changes during the last c. 7500 years as recorded by the degree of peat humification in the Lofoten region, Norway, Boreas, 41, 13-30, doi:10.1111/j.1502-3885.2011.00220.x, 2012.

Wagner, B., and Melles, M.: Holocene environmental history of western Ymer Ø, East Greenland, inferred from lake sediments, Quat. Int., 89, 165–176, doi:10.1016/S1040-6182(01)00087-8, 2002.

Wassenburg, J. A., Immenhauser, A., Richter, D. K., Niedermayr, A., Riechelmann, S., Fietzke, J., Scholz, D., Jochum, K. P., Fohlmeister, J., Schröder-Ritzrau, A., Sabaooui, A., Riechelmann, D. F. C., Schneider, L., and Esper, J.: Moroccan speleothem and tree ring records suggest a variable positive state of the North Atlantic Oscillation during the Mediaeval Warm Period, Earth Planet. Sci. Lett., 375, 291–302, doi:10.1016/j.epsl.2013.05.048, 2013.

Waterhouse, J. S., Barker, A. C., Carter, A. H. C., Agafonov, L. I. and Loader, N. J.: Stable carbon isotopes in Scots pine tree rings preserve a record of the flow of the river Ob, Geophys. Res. Lett., 27, 3529–3532, doi:10.1029/2000GL006106, 2000.

Watson, E. and Luckman, B. H.: Tree-ring based mass-balance estimates for the past 300 years at Peyto Glacier, Alberta, Canada, Quat. Res., 62, 9–18, doi:10.1016/j.yqres.2004.04.007, 2004.

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, Clim. Past, 12, 171–188, doi:10.5194/cp-12-171-2016, 2016.

Weltje, G. J.: Quantitative models of sediment generation and provenance: State of the art and future developments. Sed. Geol., 280, 4-20, doi:10.1016/j.sedgeo.2012.03.010, 2012.

Whitmore, J., Gajewski, K., Sawada, M., Williams, J. W., Minckley, T., Shuman, B., Bartlein, P. J., Webb III, T., Viau, A. E., Shafer, S., Anderson, P. and Brubaker, L.: Modern Pollen Data from North America and Greenland for Multi-scale Paleoenvironmental Applications, Quat. Sci. Rev., 24, 1828–1848, doi:10.1016/j.quascirev.2005.03.005, 2005.

Wiles, G. C., D'Arrigo, R. D., Barclay, D., Wilson, R. S., Jarvis, S. K., Vargo, L., Frank, D.: Surface air temperature variability reconstructed with tree rings for the Gulf of Alaska over the past 1200 years, Holocene, 24, 198–208, doi:10.1177/0959683613516815, 2014.

Wohlfarth, B., Holmquist, B., Cato I., Linderson, H.: The climatic significance of clastic varves in the Ångermanälven Estuary, northern Sweden, AD 1860 to 1950, Holocene, 8, 521-534, doi:10.1191/095968398668399174, 1998.

Woodhouse, C. A.: A 431-Yr Reconstruction of Western Colorado Snowpack from Tree Rings. J. Clim., 16, 1551- 1561, doi:10.1175/1520-0442-16.10.1551, 2003.

Wu, B. Y. Zhang, R. H. D'Arrigo, R. and Su, J. Z.: On the Relationship between Winter Sea Ice and Summer Atmospheric Circulation over Eurasia, J. Clim., 26, 5523–5536, doi:10.1175/JCLI-D-12-00524.1, 2013.

Yang, H., Rose N. L. and Battarbee, R. W.: Dating of recent catchment peats using spheroidal carbonaceous particle (SCP) concentration profiles with particular reference to Lochnagar, Scotland, Holocene, 11, 593-597, doi:10.1191/095968301680223549, 2001.

Yao, T., Duan, K., Xu, B., Wang, N., Gou, X. and Yang, X.: Precipitation record since 1600 from ice cores on the central Tibetan Plateau, Clim. Past, 4, 175–180, doi:10.5194/cp-4-175-2008, 2008.

Yiou, F., Raisbeck, G. M., Baumgartner, S., Beer, J., Hammer, C., Johnsen, S., Jouzel, J., Kubik, P. W., Lestringuez, J., Stiévenards, M., Suter, M. and Yiou P.: Beryllium 10 in the Greenland Ice Core Project ice core at Summit, Greenland, J Geophys. Res., 102, 26783-26794, doi:10.1029/97JC01265, 1997.

Young, G. H. F., McCarroll, D., Loader, N. J., Kirchhefer, A. J.: A 500-year record of summer near-ground solar radiation from tree-ring stable carbon isotopes, Holocene, 20, 315–324, doi:10.1177/0959683609351902, 2010.

Young, G.H.F., Loader, N.J., McCarroll, D., Bale, R. J., Demmler, J. C., Miles, D., Nayling, N. T., Rinne; K. T., Robertson, I., Watts, C. and Whitney, M.: Oxygen stable isotope ratios from British oak tree-rings provide a strong and consistent record of past changes in summer rainfall, Clim. Dyn., 45, 3609 – 3622, doi:10.1007/s00382-015-2559-4, 2015.

Young, G.H.F., McCarroll, D., Loader, N.J. Gagen, M. H., Kirchhefer, A. J. and Demmler, J. C.: Changes in atmospheric circulation and the Arctic Oscillation preserved within a millennial length reconstruction of summer cloud cover from northern Fennoscandia, Clim. Dyn., 39, 495-507, doi:10.1007/s00382-011-1246-3, 2012.

Yu, Z. C., Beilman, D.W. and Jones, M. C.: Sensitivity of northern peatlands to Holocene climate change, In: AGU Geophysical Monograph vol. 184 “Carbon Cycling in Northern Peatlands”, [Baird A, Belyea L, Comas X, Reeve A, and Slater L (eds)], pp., 55–69, 2009.

Yu, Z., Campbell, I. D., Campbell, C., Vitt, D. H., Bond, G. C. and Apps, M. J.: Carbon sequestration in western Canadian peat highly sensitive to Holocene wet-dry climate cycles at millennial time scales, Holocene, 13, 801–808, doi:10.1191/0959683603hl667ft, 2003.

Yu, Z., Campbell, I. D., Vitt, D. H. and Apps, M. J.: Modelling long-term peatland dynamics. I. Concepts, review, and proposed design, Ecol. Model., 145, 197–210, doi:10.1016/S0304-3800(01)00391-X, 2001.

Zalatan, R. and Gajewski, K.: Dendrochronological potential of Salix alaxensis from the Kuujjua River area, western Canadian Arctic, Tree-Ring Res., 62, 75–82, doi:10.3959/1536-1098-62.2.75, 2006.

Zander, P. D., Kaufman, D. S., Kuehn, S. C., Wallace, K. L. and Anderson, R. S.:. Early and late Holocene glacial fluctuations and tephrostratigraphy, Cabin Lake, Alaska, J. Quat. Sci., 28, 761-771, doi:10.1002/jqs.2671, 2013.

Zeeberg, J. and Forman, S. L.: Changes in glacier extent on north Novaya Zemlya in the twentieth century, Holocene, 11, 161-175, doi:10.1191/095968301676173261, 2001.

Zemp, M., Hoelzle, M. and Haeberli W.: Six decades of glacier mass-balance observations: a review of the worldwide monitoring network, Ann. Glaciol., 50, 101-111, doi:10.3189/172756409787769591, 2009.

Zhang, H., Amesbury, M., Ronkainen, T., Charman, D. J., Gallego-Sala, A.V. and Väliranta, M. 2017. Testate amoeba as palaeohydrological indicators in the permafrost peatlands of Northeast European Russia and Finnish Lapland, J. Quat. Sci., doi:10.1002/jqs.2970, 2017.

Zhang, X., He, J., Zhang, J., Polyakov, I., Gerdes, R., Inoue, J. and Wu, P.: Enhanced poleward moisture transport and amplified northern high-latitude wetting trend, Nat. Clim. Chang., 3, 47–51, doi:10.1038/nclimate1631, 2013.

Zwiers, F. W.: A potential predictability study conducted with an atmospheric general circulation model, Mon. Wea. Rev., 115, 2957–2974, doi:10.1175/1520-0493(1987)115<2957:APPSCW>2.0.CO;2, 1987.

Tables

Table 1. Regional (shown in Figure 5) and site-specific (Fig 6) precipitation reconstructions of the past two millennia from North America.

Site	Proxy/Indication	Reference	Data availability
Beringia	Pollen	Viau et al. (2008)	https://www.ncdc.noaa.gov/paleo/study/8689 or http://www.lpc.uottawa.ca/data/reconstructions/index.html
Mackenzie, Central, Quebec, Labrador	Pollen	Viau et al. (2009)	https://www.ncdc.noaa.gov/paleo/study/8690 or http://www.lpc.uottawa.ca/data/reconstructions/index.html
BC01 (Melville Island)	Pollen	(Peros et al., 2010)	http://www.lpc.uottawa.ca/data/reconstructions/index.html
MB01 (western Victoria Island)	Pollen	(Peros et al., 2009)	https://www.ncdc.noaa.gov/paleo/study/6200 or http://www.lpc.uottawa.ca/data/reconstructions/index.html
KR02 (western Victoria Island)	Pollen	(Peros et al., 2008)	https://www.neotomadb.org/ Dataset 20649 or http://www.lpc.uottawa.ca/data/reconstructions/index.html
SL06 (Boothia Peninsula)	Pollen	(Peros et al., 2009)	https://www.ncdc.noaa.gov/paleo/study/6200 or http://www.lpc.uottawa.ca/data/reconstructions/index.html

Table 2. Characterization of Nordic proxy records from Sweden (SWE) and Finland (FIN) indicative of hydroclimatic variations over the Common Era.

Site	Code	Lat/Long	Proxy/Indication	Res	Reference	Data availability
Håckren	SWE 01	63.17 13.50	Tree accumulation/ Lake level	1	Gunnarson et al., (2003); Gunnarson (2008)	http://bolin.su.se/data/Gunnarson-2017
Backsjömyren	SWE 02	62.68 14.53	Peat humification/ Peatland water table	40	Andersson & Schoning (2010);	Data are on the way….
Stömyren	SWE 03	60.38 15.27	Peat humification/ Peatland water table	40	Gunnarson et al., (2003)	https://www1.ncdc.noaa.gov/pub/data/paleo/reconstructions/hydroclimate/ljungqvist2016/hydro_proxies/Stomyren.txt
Vuoksjávrátje	SWE 04	66.25 15.72	Si/Ti (coarse grain size)/ Flooding	1.5	Berntsson et al., (2015)	https://www.ncdc.noaa.gov/paleo/study/22253
Vuoksjávrátje	SWE 05	66.25 15.72	Chironomids/ Catchment erosion	80	Berntsson et al., (2015)	https://www.ncdc.noaa.gov/paleo/study/22253
Kontolanrahka	FIN 06	60.78 22.78	Plant macrofossils/ Peatland water table	10	Väliranta et al., (2007)	http://www.helsinki.fi/science/dendro/data/fennoscandian-hydroclimate.xls
Iso Lehmälampi	FIN 07	60.33 24.60	Cladocera/ Water depth (intralake)	80	Nevalainen & Luoto (2012)	https://www.ncdc.noaa.gov/paleo/study/22212
Iso Lehmälampi	FIN 08	60.33 24.60	Cladocera/ Water depth (multilake)	80	Nevalainen et al., (2011)	https://www.ncdc.noaa.gov/paleo/study/22212
Iso Lehmälampi	FIN 09	60.33 24.60	Chironomids/ Lake water depth	80	Luoto (2009)	https://www.ncdc.noaa.gov/paleo/study/22212
Kalliojärvi	FIN 10	63.22 25.37	Varve light sum/ Spring floods	1	Saarni et al., (2016)	https://www.ncdc.noaa.gov/paleo/study/22194
Kallio-Kourujärvi	FIN 11	62.57 27.00	Varve thickness/ Precipitation	1	Saarni et al., (2015)	https://www.ncdc.noaa.gov/paleo/study/22193
SE Finland	FIN 12	61.95 28.97	Tree accumulation/ Lake water depth	1	Helama et al., (2017)	http://www.helsinki.fi/science/dendro/data/fennoscandian-hydroclimate.xls
SE Finland	FIN 13	61.80 29.75	Tree accumulation/ Peatland water table	1	Helama et al., (2017)	http://www.helsinki.fi/science/dendro/data/fennoscandian-hydroclimate.xls
Pieni-Kauro	FIN 14	64.28 30.12	Cladocera/ Lake water depth	40	Nevalainen et al., (2013)	https://www.ncdc.noaa.gov/paleo/study/22213
Pieni-Kauro	FIN 15	64.28 30.12	Chironomids/ Stream flow	40	Luoto & Helama (2010)	https://www.ncdc.noaa.gov/paleo/study/22213
Kylmänlampi	FIN 16	64.30 30.25	Chironomids/ Lake water depth	100	Luoto & Nevalainen (2015)	https://www.ncdc.noaa.gov/paleo-search/study/22211

Table 3. Hydroclimate proxy records available for the Arctic area. Except for annually resolved series, the resolutions given correspond to a mean. The asterisks indicate (*) series used by Ljungqvist et al. (2016, data available at https://www.ncdc.noaa.gov/paleo/study/19725); (**) indicates series from Weißbach et al. (2016, data available at https://doi.pangaea.de/10.1594/PANGAEA.849161); and (***)from Sundqvist et al. (2016, data available at doi:10.5194/cp-10-1605-2014-supplement). The series used in the qualitative hydroclimate reconstruction are shown in bold.

ID	Region		Site	Lat (°N)	Long (°E)	Archive	Proxy	Oldest	Youngest	Resolution (years)	Original reference
Hydro2k_01	Greenland	***	N14	59,98	-44,18	Lake	BSi	11	1480	33	Anderson et al., 2004
Hydro2k_02	NW Norway	***	Fiskebølvatnet	68,413	14,802	Lake	Mass Acc. Rate	786	1569	17	Balascio and Bradley, 2012
Hydro2k_03	SE Norway	***	Nattmålsvatn	69,1793	17,3943	Lake	MS (SI)	6	849	NA	Janbu et al., 2011
Hydro2k_04	**N Alaska**	**	**Wolverine Lake**	**67,098**	**-158,914**	**Lake**	**Mass Acc. Rate**	**800**	**1926**	**31**	**Mann et al. 2002**
Hydro2k_05	N Norway	***	Rystad 1	68,2389	13,7839	Peat	Humification	776	1646	827,5	Vorren et al. 2012
Hydro2k_06	W Greenland	***	SS16	66,91	-50,46	Lake	Diatom	820,9	1999,6	26,8	Perren et al. 2012
Hydro2k_07	**C Sweden**	**	**Stömyren**	**60,2083**	**13,4667**	**Peat**	**Humification**	**794**	**1928**	**37**	**Borgmark and Wastegård, 2008**
Hydro2k_08	W Greenland	***	SS1381	67,014	-51,102	Lake	Mineral flux	795	1811	41	Anderson et al. 2012
Hydro2k_09	W Hudson Bay	***	Unit Lake	59,404	-97,493	Lake	AMR/IRM	799	2010	71	Camill et al. 2012
Hydro2k_10	E Finland	***	Saarikko	62,25	27,67	Lake	$d^{18}O$	788	1822	47	Heikkilä et al. 2010
Hydro2k_11	N Norway	**	Over Gunnarsfjorden	71,0383	28,1685	Lake	Pollen	814	1989	49	Allen et al. 2007
Hydro2k_12	N Norway	***	Sellevollmyra	69,1083	15,9417	Peat	Humification	798	1495	69	Vorren et al. 2007
Hydro2k_14	**Greenland**	**	**Crête**	**71,12**	**-37,32**	**Ice**	**Lamina**	**800**	**1973**	**1**	**Andersen et al., 2006**
Hydro2k_15	**Grennland**	**	**Dye 3**	**65,11**	**-43,49**	**Ice**	**Lamina**	**800**	**1978**	**1**	**Andersen et al., 2006**
Hydro2k_16	**Canada**	**	**East Lake**	**74,88**	**-109,53**	**Lake**	**Lamina**	**800**	**2005**	**1**	**Cuven et al., 2011**
Hydro2k_17	**Greenland**	**	**GISP2**	**72,6**	**-38,5**	**Ice**	**Lamina**	**800**	**1987**	**1**	**Meese et al., 1994**
Hydro2k_18	**Greenland**	**	**GRIP**	**72,35**	**-37,38**	**Ice**	**Lamina**	**800**	**1979**	**1**	**Andersen et al., 2006**
Hydro2k_19	**Greenland**	**	**NGRIP**	**75,1**	**-42,32**	**Ice**	**Lamina**	**800**	**1995**	**1**	**Andersen et al., 2006**
Hydro2k_20	**Alaska**	**	**Dune Lake**	**64,42**	**-149,9**	**Lake**	**$d^{13}C$**	**795**	**1992**	**16**	**Finney et al., 2012**
Hydro2k_21	**Alaska**	**	**Ongoke Lake**	**59,25**	**-159,42**	**Lake**	**Diatom**	**498**	**2004**	**15**	**Chipman et al., 2009**
Hydro2k_22	**Canada**	**	**Marcella Lake**	**60,07**	**-133,81**	**Lake**	**$d^{18}O$**	**798**	**2008**	**10**	**Andersen et al., 2007**
Hydro2k_23	**N Norway**	**	**Nerfloen Lake**	**61,93**	**6,87**	**Lake**	**Particle size**	**786**	**1969**	**25**	**Vasskog et al., 2012**
Hydro2k_24	Greenland	***	Milcent	70,3	-44,55	Ice	Acc. Rate	1174	1966	1	Andersen et al., 2006
Hydro2k_27	Alaska	***	Takahula Lake	67,35	-153,66	Lake	$d^{18}O$.calcite	753	2001	50	Clegg and Hu, 2010
Hydro2k_31	**E Finland**	**	**Pieni-Kauro Lake**	**64,28**	**30,12**	**Lake**	**Chironomid**	**800**	**1990**	**46**	**Luoto et Helama, 2010**
Hydro2k_32	**Finland**	**	**Southern Finland**	**61,5**	**28,5**	**Trees**	**Ring width**	**800**	**1993**	**1**	**Helama et al., 2009**
Hydro2k_34	**S Sweden**	**	**Fågelmossen 1**	**59,29**	**14,27**	**Peat**	**Humification**	**794**	**1914**	**15**	**Borgmark and Wastegård, 2008**
Hydro2k_35	**S Sweden**	**	**Fågelmossen 2**	**59,29**	**14,27**	**Peat**	**Humification**	**793**	**1967**	**12**	**Borgmark and Wastegård, 2008**
Hydro2k_37	**Finland**	**	**Kontolanrahka Lake**	**60,78**	**22,78**	**Peat**	**Humification**	**750**	**1913**	**30**	**Vairanta et al., 2007**
Hydro2k_38	Greenland	**	NGT B16	73,9	-37,6	Ice core	Acc. Rate	1471	1992	1	Weisbach et al., 2016

Hydro2k_39	Greenland	**	NGT B17	75,25	-37,62	Ice core	Acc. Rate	1363	1992	1	Weisbach et al., 2016
Hydro2k_40	Greenland	**	NGT B18	76,61	-36,4	Ice core	Acc. Rate	874	1992	1	Weisbach et al., 2016
Hydro2k_41	Greenland	**	NGT B19	78	-36,39	Ice core	Acc. Rate	753	1953	1	Weisbach et al., 2016
Hydro2k_42	Greenland	**	NGT B20	78,83	-36,5	Ice core	Acc. Rate	775	1993	1	Weisbach et al., 2016
Hydro2k_43	Greenland	**	NGT B21	80	-41,1	Ice core	Acc. Rate	1372	1993	1	Weisbach et al., 2016
Hydro2k_44	Greenland	**	NGT B22	79,34	-45,91	Ice core	Acc. Rate	1372	1993	1	Weisbach et al., 2016
Hydro2k_45	Greenland	**	NGT B23	78	-44	Ice core	Acc. Rate	1023	1993	1	Weisbach et al., 2016
Hydro2k_46	Greenland	**	NGT B26	77,25	-49,21	Ice core	Acc. Rate	1505	1994	1	Weisbach et al., 2016
Hydro2k_48	Greenland	**	NGT B29	76	-43,49	Ice core	Acc. Rate	1471	1994	1	Weisbach et al., 2016
Hydro2k_49	Greenland	**	NGT B30	75,01	-42	Ice core	Acc. Rate	1242	1988	1	Weisbach et al., 2016

Table 4. PMIP3 climate models used in this study. The spatial resolution of atmosphere is expressed by the number of longitudinal grid cells × the number of latitudinal grid cells.

Model	Institute/Country	Spatial resolution of atmosphere
HadCM3	MOHC/UK	96×73
IPSL-CM5A-LR	IPSL/France	96×95
MPI-ESM-P	MPI-M/Germany	196×98

Figures

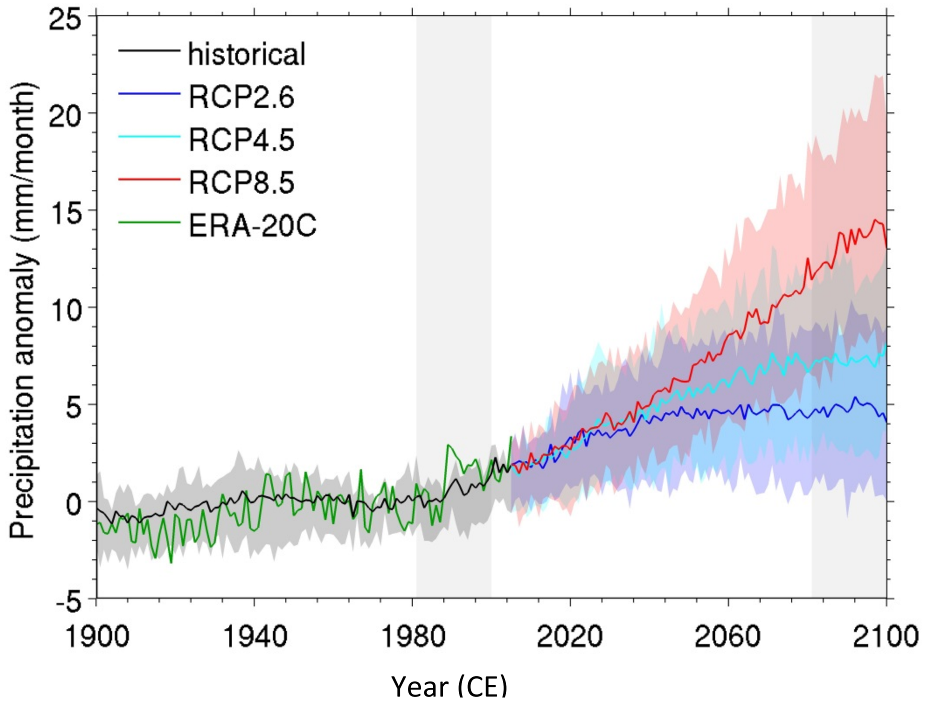

Figure 1. Annual precipitation anomaly (relative to the period 1961-1990) of the Arctic region (>= 60°N) derived from ensemble mean of historical (1900-2005) and RCP (2006-2100) simulations using 12 CMIP5 climate models (Taylor et al., 2012). The green line shows the annual precipitation anomaly derived from the ERA-20C reanalysis dataset (Poli et al., 2013). Solid lines represent multi-model ensemble means, while shadings around the solid lines represent the interquartile ensemble spreads (25th and 75th quartiles). The two vertical light gray shadings mark the time period of 1981-2000 (left) and 2081-2100 (right).

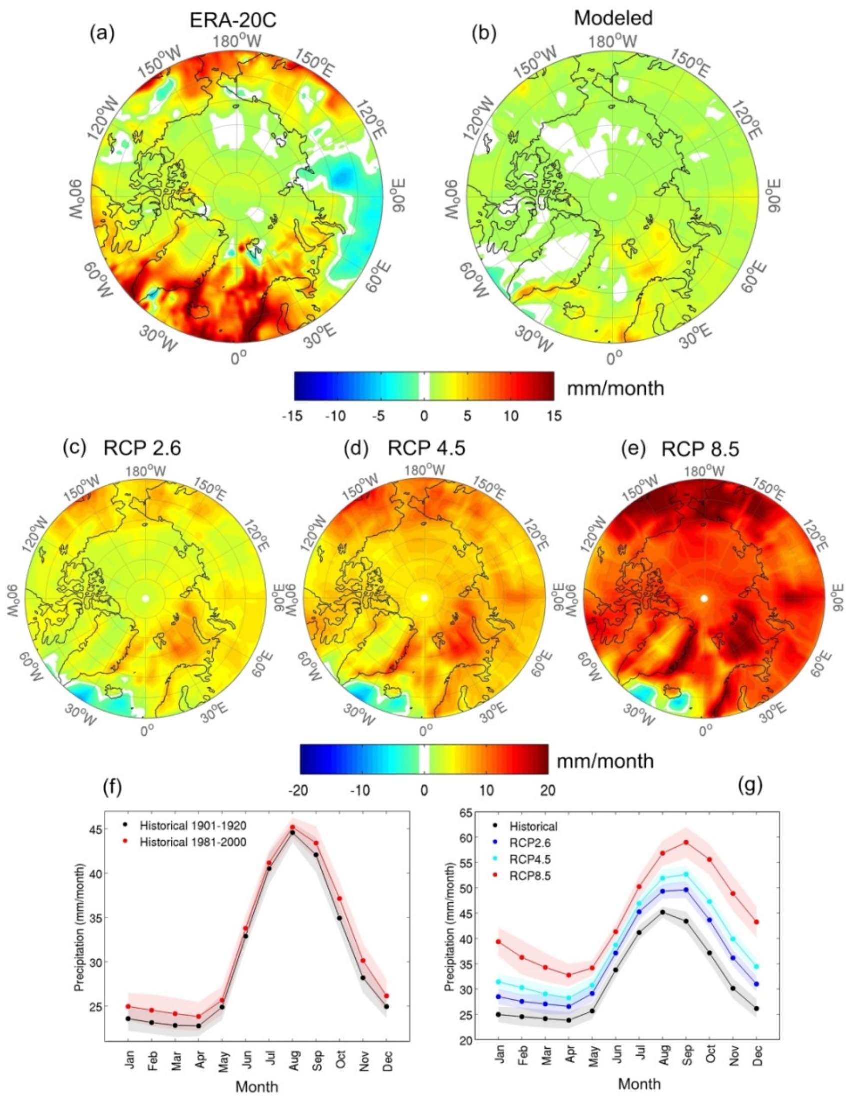

Figure 2. Modeled and observed Arctic precipitation. Upper panel: a) observed and b) modeled changes in annual precipitation over the Arctic region (>= 60°N) relative to the reference period 1901-1920 and averaged over the 1981-2000 period. The observed pattern is obtained from the ERA-20C reanalysis dataset (Poli et al., 2013). The modeled pattern is derived from ensemble mean of historical (1900-2005) simulations performed by 12 CMIP5 climate models (Taylor et al., 2012); Middle panel: Multi-model (12 CMIP5 models) average changes in annual precipitation relative to the reference period 1981-2000 averaged over the period 2081-2100 under RCP2.6 (c), RCP4.5 (d) and RCP8.5 (e) forcing scenarios; Lower panel: Multi-model (12 CMIP5 models) average of seasonal cycle of precipitation over the Arctic region (>= 60°N) over the periods of 1901-1920 (black) and 1981-2000 (red) (f), and over the periods of 1981-2000 (black) and 2081-2100 (other colors) (g). Solid lines represent multi-model ensemble means, while shadings around the solid lines represent uncertainties expressed as ±2 times the standard deviation of the mean monthly precipitation over a 20-years period.

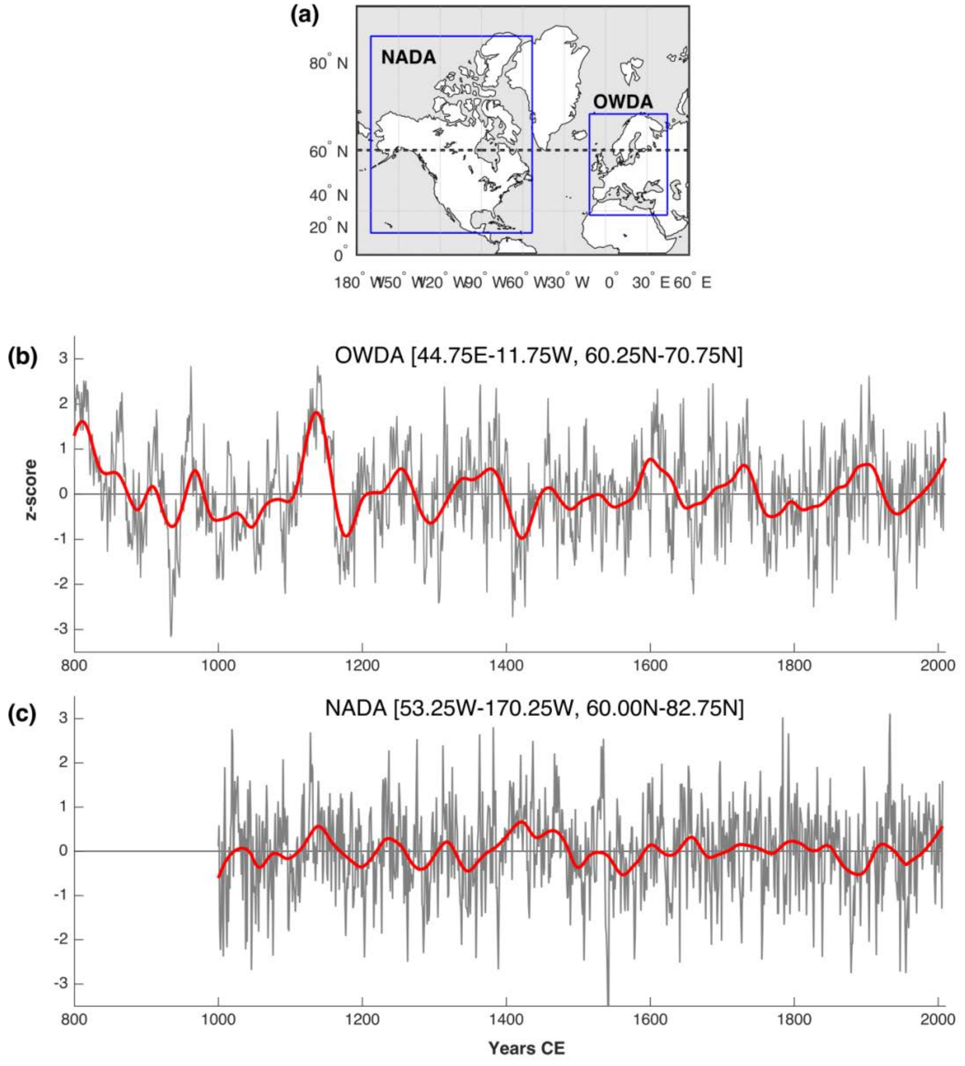

Figure 3. North American (NADA, Cook et al., 2004, https://www.ncdc.noaa.gov/paleo/study/6319) and Old World (OWDA, Cook et al., 2015, https://www.ncdc.noaa.gov/paleo/study/19419) Drought Atlas reconstructions over the Arctic region. (a) The full spatial domains of the two atlases; and regional average over latitudes > 60°N in (b) Europe and (c) North America, transformed into z-scores and filtered with a filtered with a 100-year loess filter (red lines).

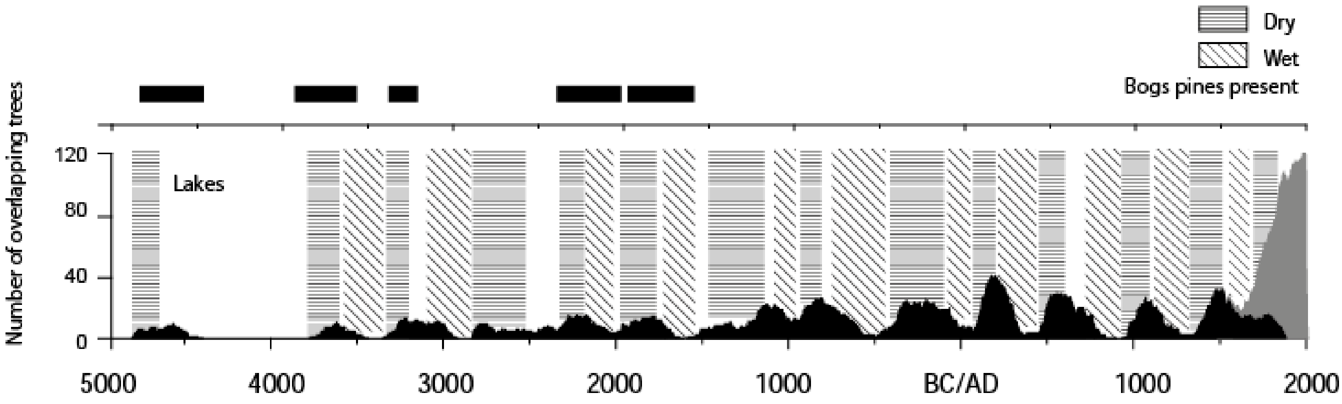

Figure 4. Changes in Scots pine sample depth through time for subfossil Scots pines (black) from lakes in the central Scandinavian Mountains (Gunnarson 2008). The grey shaded area at the end represents living trees. Interpreted wet and dry periods are sown in grey breaks as well as the presence of Scots pines growing on a nearby peat bog indicating drier conditions (Adapted from Gunnarson 2008). Data available at http://bolin.su.se/data/Gunnarson-2017.

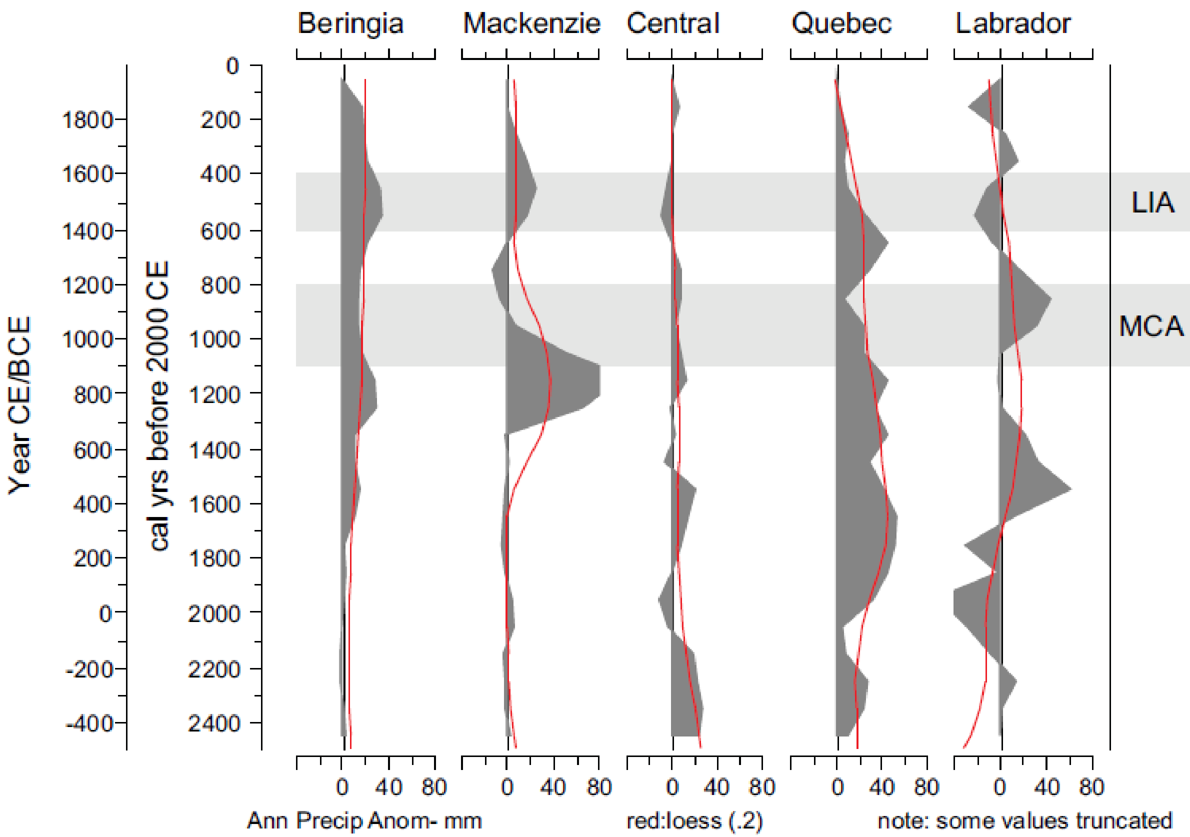

Figure 5. Regional reconstructions of annual precipitation from the boreal zone of North America. The average of all pollen records from the different regions are shown. Beringia (Alaska), Mackenzie (western Yukon), Central Canada, Quebec and Labrador. The Beringa record is described in Viau et al. (2008) and the others in Viau et al. (2009). See table 1 for data availability.

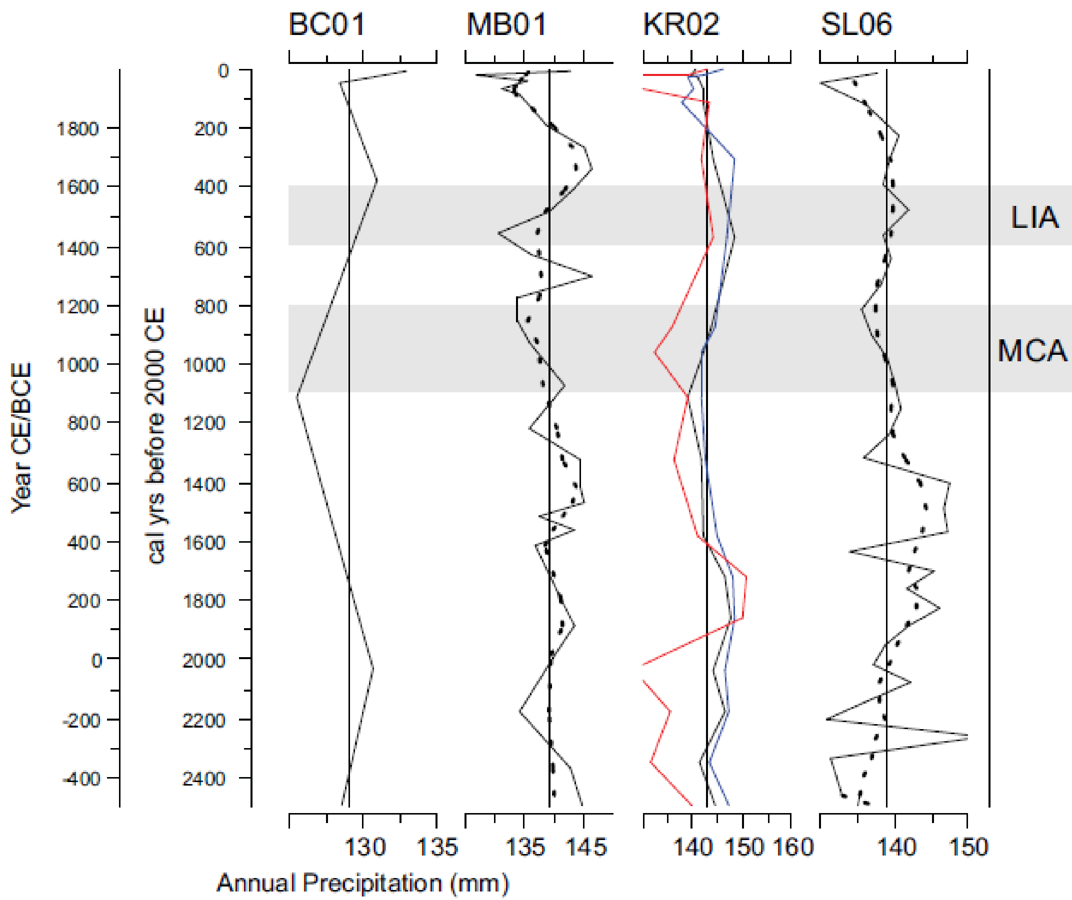

Figure 6. Annual precipitation reconstructions, based on pollen assemblages, from four sites in the Canadian Arctic. BC01 (Peros et al., 2010): Melville Island; MB01 (Peros et al., 2009) and KR02 (Peros et al., 2008): western Victoria Island; SL06 (Peros et al., 2009): Boothia Peninsula. Dotted lines are loess smoothed. For Lake KR02: red=Modern analogue technique, blue=WAPLS, black=PLS. See Table 1 for information on data availability.

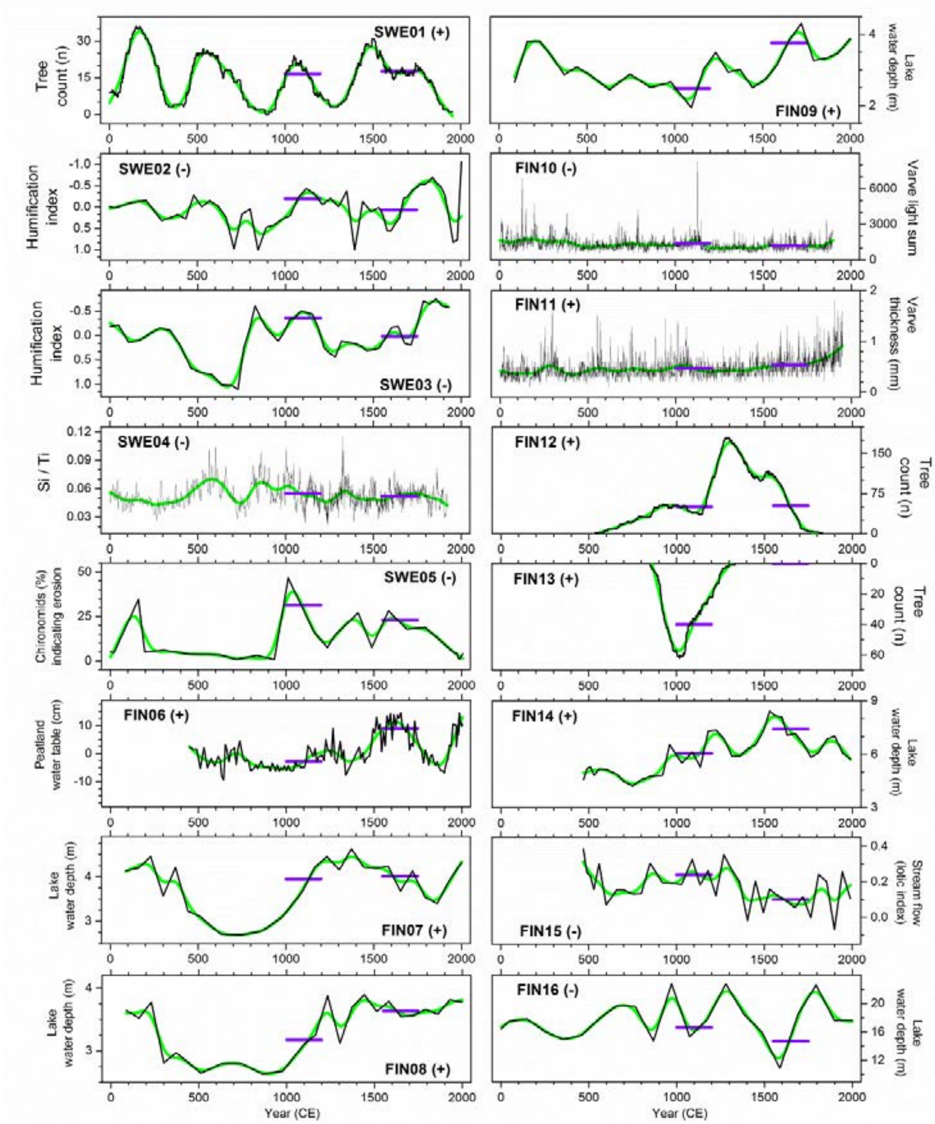

Figure 7. Hydroclimatic variations in the Nordic proxy records from Sweden (SWE) and Finland (FIN) over the Common Era (see Table 2 for detailed information and information on data availability). The mean levels (violet line) during the Mediaeval Climate Anomaly (MCA) and Little Ice Age (LIA) were calculated from the published records (black line), those being additionally smoothed using 200-year spline function (green line). Proxy data indicating change from MCA towards wetter (drier) LIA conditions are noted by plus (minus) sign. The graphs have been arranged so that wet conditions are indicated upward and dry conditions downward change in the figure.

Figure 8. Spatial distribution of the hydroclimate proxy records available in the Arctic region. Records used for the new synthesis are highlighted by larger symbols and black borders. For information on the records, see Table 3.

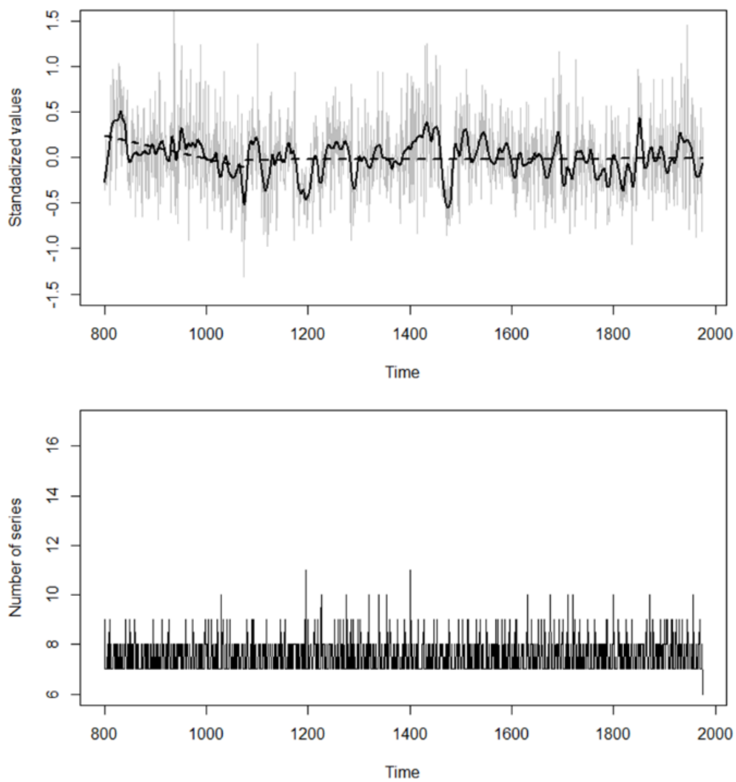

Figure 9. Upper panel: Mean Pan-Arctic hydroclimate index (grey line) based on 17 selected series (Table 3). The thick black line is a 30-year LOESS filter, and the dashed lines linear trends determined by a Mann-Kendall test. Data are presented as standardized (z-scored) values. Lower panel: Number of time series through time included in the synthesis.

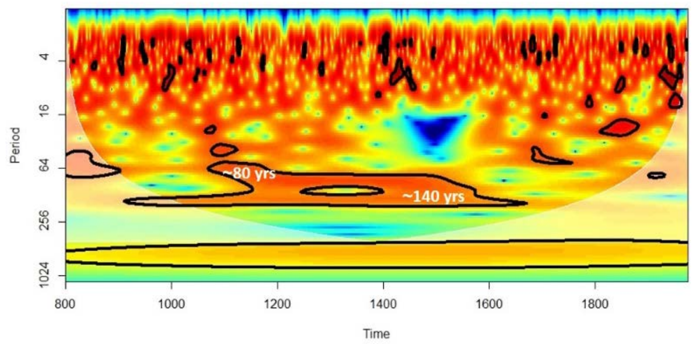

Figure 10. Wavelet analysis of the Pan-Arctic hydroclimate record. Colors represent the amplitude of the signal at given time and spectral period (red equals highest power, blue lowest). White line corresponds to cone of influence on wavelet coherence spectrum and global wavelet spectrum. Confidence levels of 95% (α=0.05) are indicated on the wavelet spectrum with the black lines.

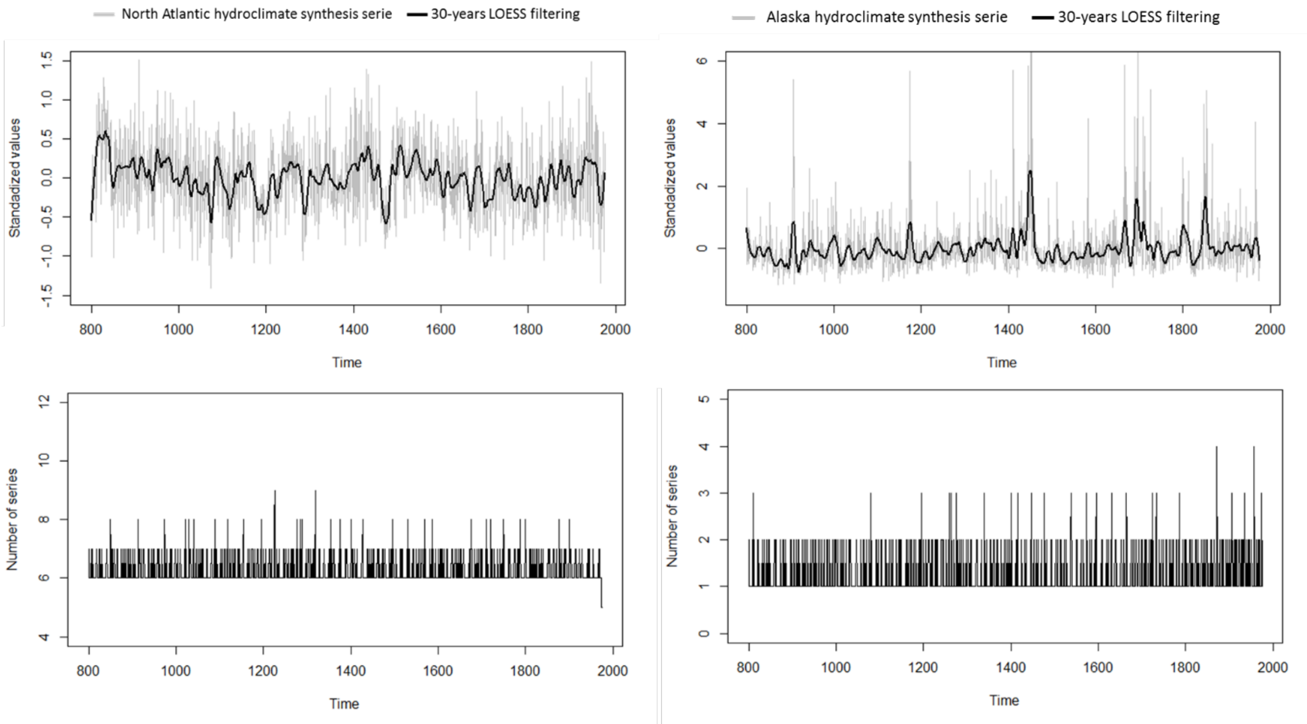

Figure 11. Regional hydroclimate mean records (grey) with 30-year loess filters in black for the North Atlantic region (upper left) and Alaska (upper right). Data are presented as standardized (z-scored) values. Lower panels show the corresponding numbers of records through time included in the synthesis (see Table 3 for information on the records)

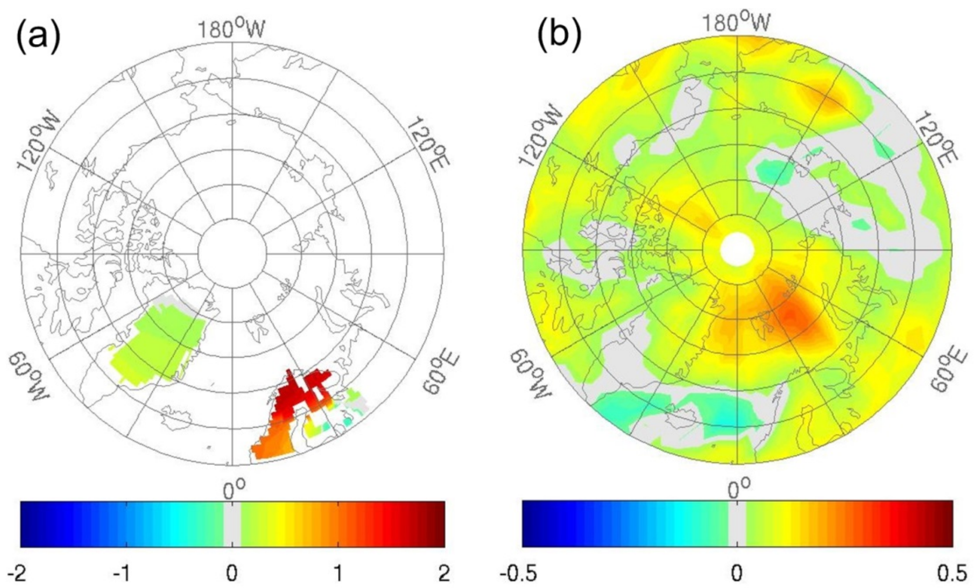

Figure 12. Spatial pattern of differences in annual hydroclimate between MCA (950-1250 CE) and LIA (1450-1850 CE) based on (a) hydroclimate reconstruction (Ljungqvist et al., 2016) and (b) ensemble mean of 3 last-millennium simulations. The values in (a) are z-scores of the hydroclimate index, while those in (b) are z-scores of the annual total precipitation. The z-scores are based on the period 850-1850 CE.

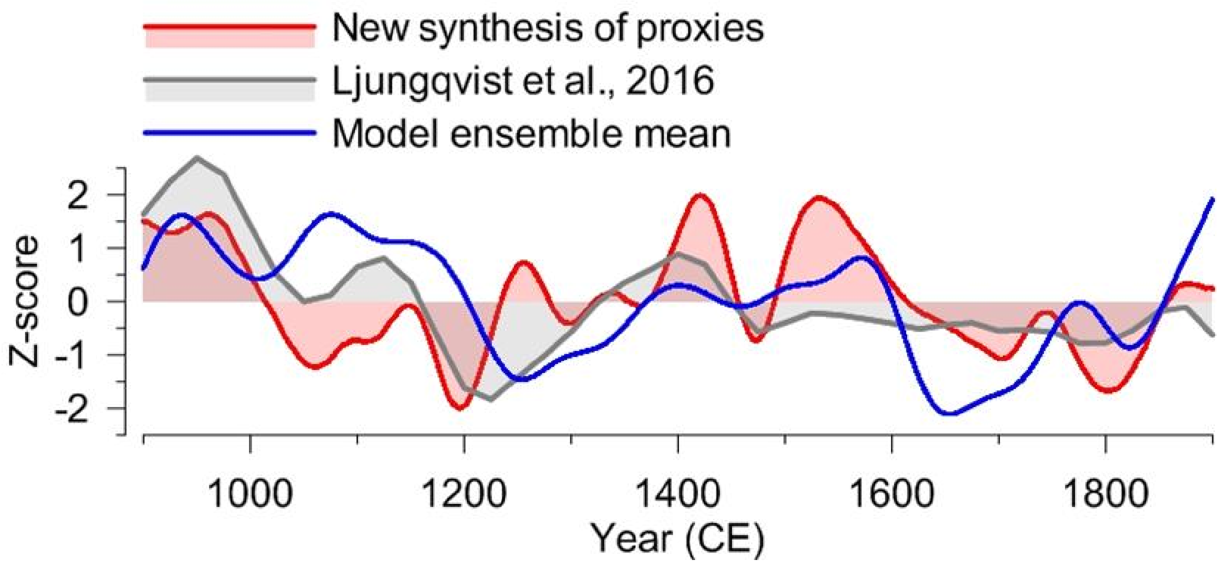

Figure 13. Comparison of centennial-scale annual hydroclimate variability (after application of a Gaussian filter) over the Arctic (≥ 60°N) North Atlantic region from a reconstruction by Ljungqvist et al. (2016, grey), the new Pan-Arctic hydroclimate proxy synthesis (red) and an ensemble mean of 3 last-millennium precipitation simulations (blue). See the main text for more information.

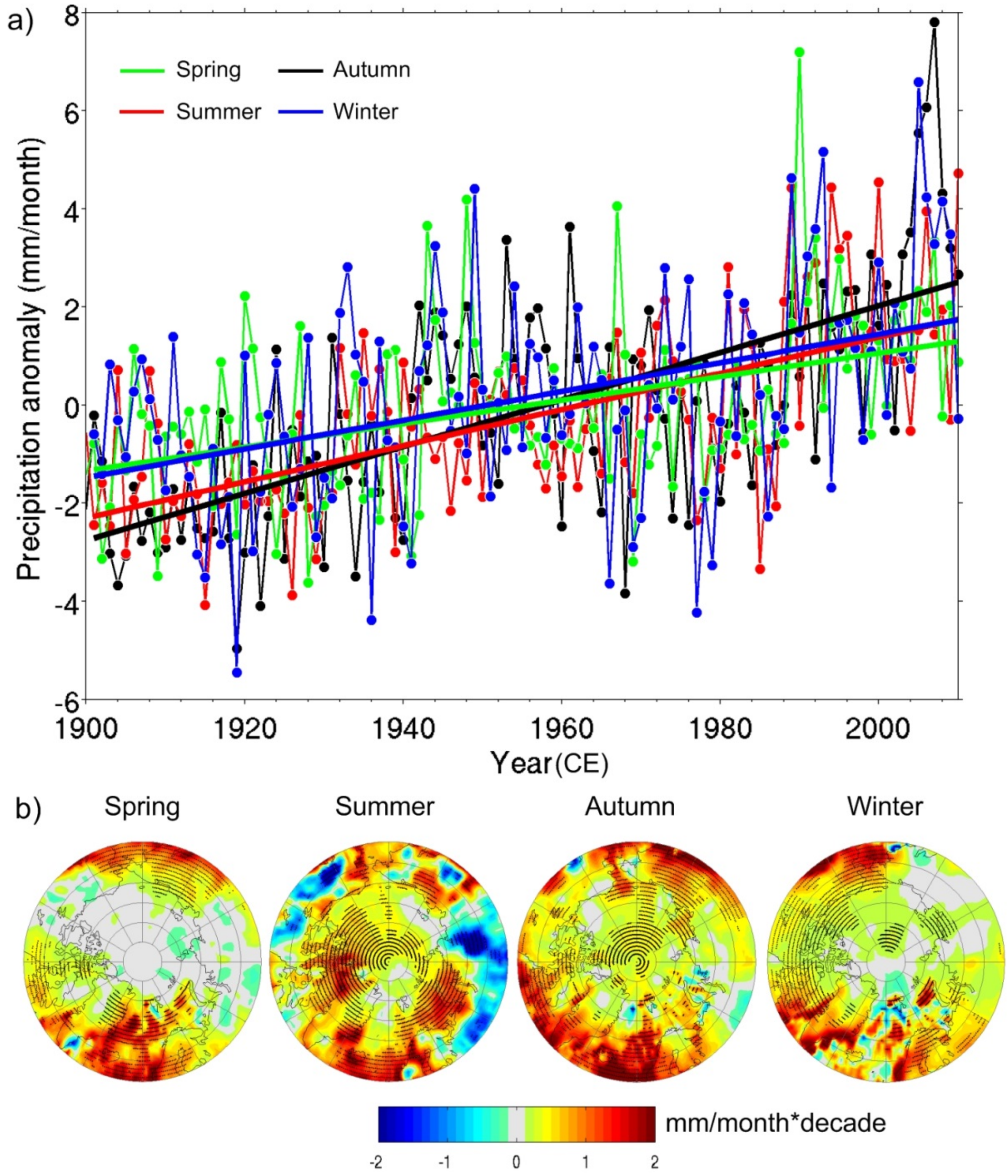

Figure 14. a) Variability and linear trends of the Arctic spring, summer, autumn and winter total precipitation anomalies over the period 1900-2010 from the ERA-20C reanalysis dataset (Poli et al. 2013). b): Spatial patterns of linear trends of the Arctic spring, summer, autumn and winter total precipitation anomalies over the period1900-2010. Shadings marks those grid cells where the trend is significant (p<0.01).

Supplementary material

Table S1 Twelve CMIP5 climate models used in this study. The spatial resolution of atmosphere is expressed by the number of longitudinal grid cells × the number of latitudinal grid cells.

Model	Institute/Country	Spatial resolution of atmosphere
GFDL-CM3	NOAA GFDL/USA	144×90
GFDL-ESM2G	NOAA GFDL/USA	144×90
GFDL-ESM2M	NOAA GFDL/USA	144×90
GISS-E2-H	NASA GISS/USA	144×90
GISS-E2-R	NASA GISS/USA	144×90
HadGEM2-AO	MOHC/UK	192×145
HadGEM2-ES	MOHC/UK	192×145
MIROC5	MIROC/Japan	256×128
MIROC-ESM	MIROC/Japan	128×64
MIROC-ESM-CHEM	MIROC/Japan	128×64
MRI-CGCM3	MRI/Japan	320×160
NorESM1-ME	NCC/Norway	144×96

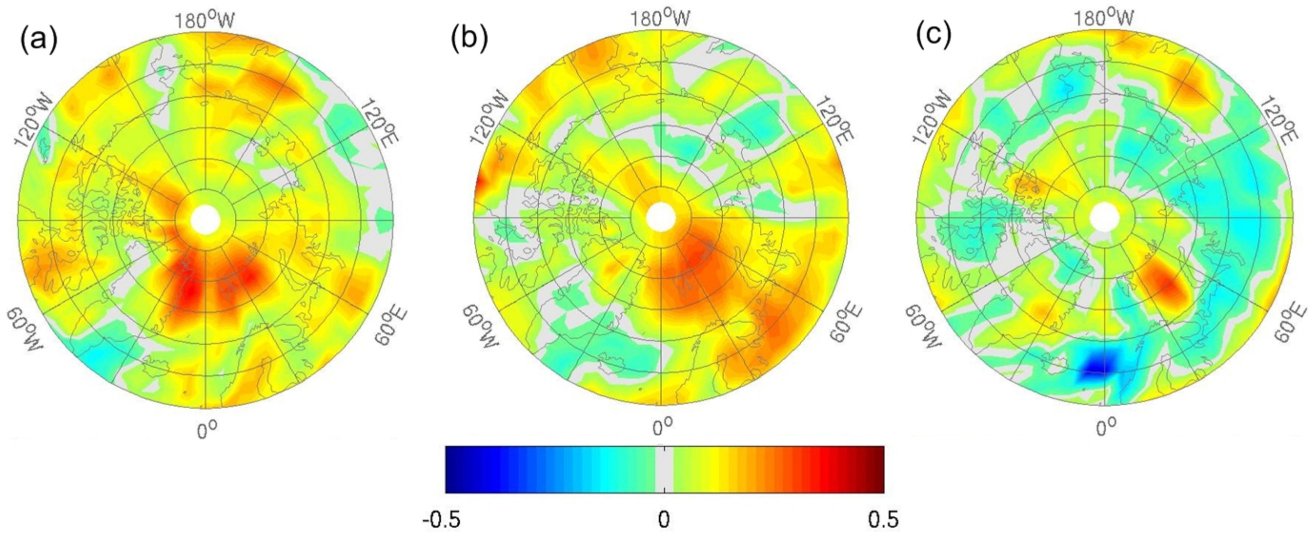

Figure S1. Spatial pattern of differences in annual hydroclimate between MCA (950-1250) and LIA (1450-1850) based on (a) HadCM3, (b) IPSL-CM5A-LR and (c) MPI-ESM-P last-millennium simulations. The values are z-score (based on the period 850-1850 CE) of the annual total precipitation.

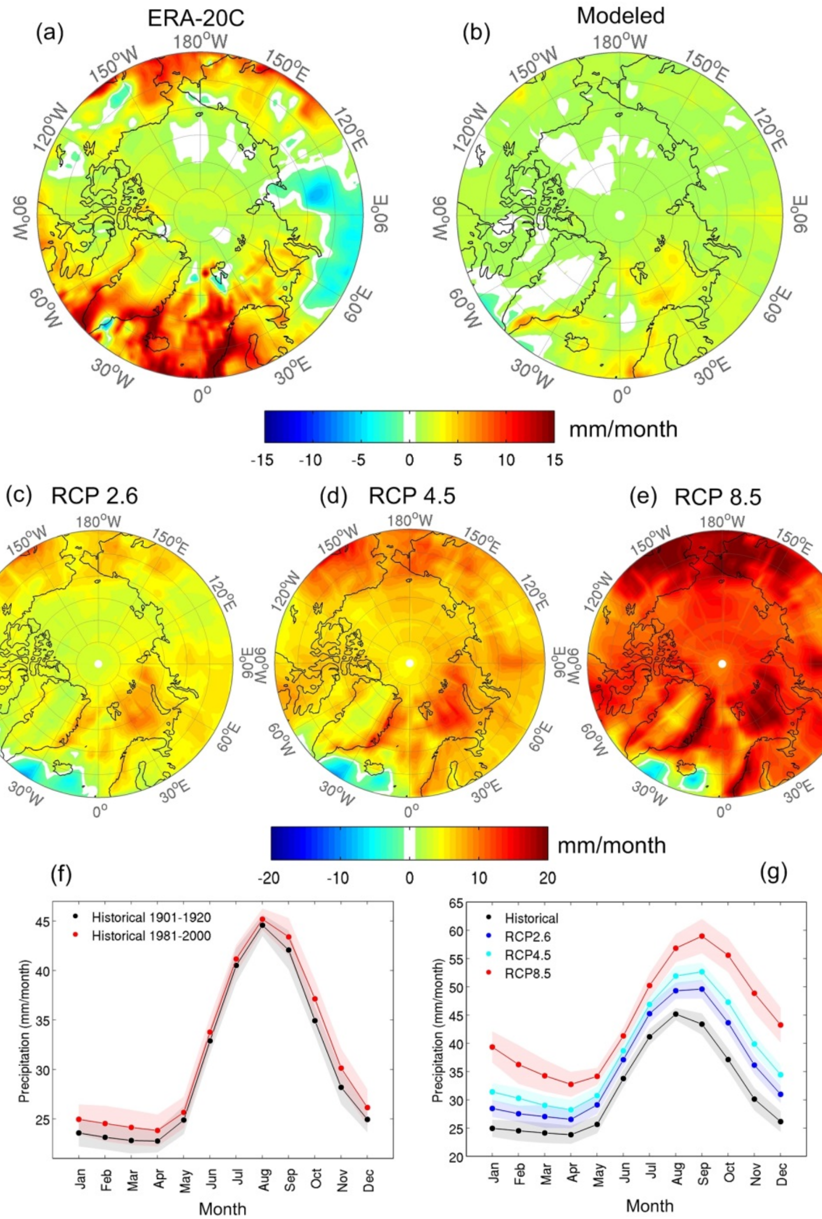

Figure S2. a) Variability and linear trends of the Arctic spring, summer, autumn and winter total precipitation anomalies (900-1900 CE) from 3-model (HadCM3, IPSL-CM5A-LR and MPI-ESM-P) ensemble mean. b) Spatial patterns of linear trends in seasonal total precipitation anomalies over (900-1850 CE) from 3 climate models. Shadings marks those grid cells where the trend is significant (p<0.01).