Dear Editor,

Please find in attachment, the manuscript entitled "A millennial summer temperature reconstruction for northeastern Canada using oxygen isotopes in subfossil trees" in the submitted version and in a marked version (indicating the added information). The paper has been modified following the comments submitted in the interactive discussion by R. Way and two referees (N. Loader and H. Linderholm). We have also added a supplementary material that brings much more information about tree-ring sampled and i-STREC data. Overall, we think that the article is greatly improved and we submit this version for publication.

The comments submitted in interactive discussion appear in blue whereas our responses are in black. Every response is numbered following the order of the comments. We thank the referees and the R. Way for their useful comments and suggestions, our answers are listed below.

M. Naulier

Comment from R. Way

[1.1] In particular, I noted that the authors do not provide comparisons with the D'Arrigo et al (1996, 2003). Tree ring record from northern Labrador which provides somewhat different results;

We are well aware of the series produced by d'Arrigo *et al*. (1996, 2003). These authors have reconstructed mean summer temperature over the last four centuries. This series and many others in the literature are of interest but do not cover the last millennium. The reader has to keep in mind that our discussion compares our 1000 years-long reconstruction, i-STREC with six other millennial series. That way our discussion is not too long; a long discussion being unnecessary (see review by H. Linderholm).

[1.2] Many of the interpretations provided in the text and some of the information would benefit by comparison with the results of Way and Viau (in press) which characterizes the regional drivers of climate variability in Labrador over the past century. This work is relatively recent and has only been online since August of 2014 but it certainly would reinforce and help with the interpretation of results;

The Way and Viau paper (2014) appears as an interesting discussion helping to understand forcings that controlled air temperature of the last century in Labrador, with a rapid increase during the last 17 years. Such suggestions could apply in part for the warming observed in northeastern Canada. Therefore, we have added this reference and we now allude to this possibility for the warming observed in the study region during the last three decades (lines 360-370): "Nevertheless, the causes that triggered these periods are likely different (i.e., Landrum *et al.,* 2013; Way and Viau, 2014). Indeed, if the MWA is only controlled by natural processes, it seems that the warming of the modern period results from a combination of natural and anthropogenic causes (i.e, Mann *et al*., 2009). By using empirical statistical modeling and global climate models, Way and Viau (2014) have shown that the variance of annual air temperature over the period 1881-2011 in Labrador was explained at 65% if anthropogenic forcing was also included in the model. Even if summer temperature has increased at a lower rate compared to annual air temperature in Labrador, the observed warming (+1.9°C) between 1970 and 2000 is one of the fastest over the last millennium in the region of L20. In the next decades, if warming continues at this rate, temperature will reach a record for the last millennium."

[1.3] An additional point of discussion is the authors provide information of the role that multidecadal variability plays in the region relative to their results and particularly with respect to whether it is detectable in the air temperature reconstruction provided - I believe noting this type of variability would add to the discussion - does the reconstruction agree well with AMO reconstructions for instance?;

We have examined the links between i-STREC and AMO series for various months (see Figure I below), and the correlations obtained over the recent 143 years are not stable over time (vary from positive to negative, and from significant to non-significant). Consequently, the control of the AMO on temperature in northeastern Canada is not suggested by our reconstruction, and AMO does not appear as relevant for the discussion of potential main forcings.

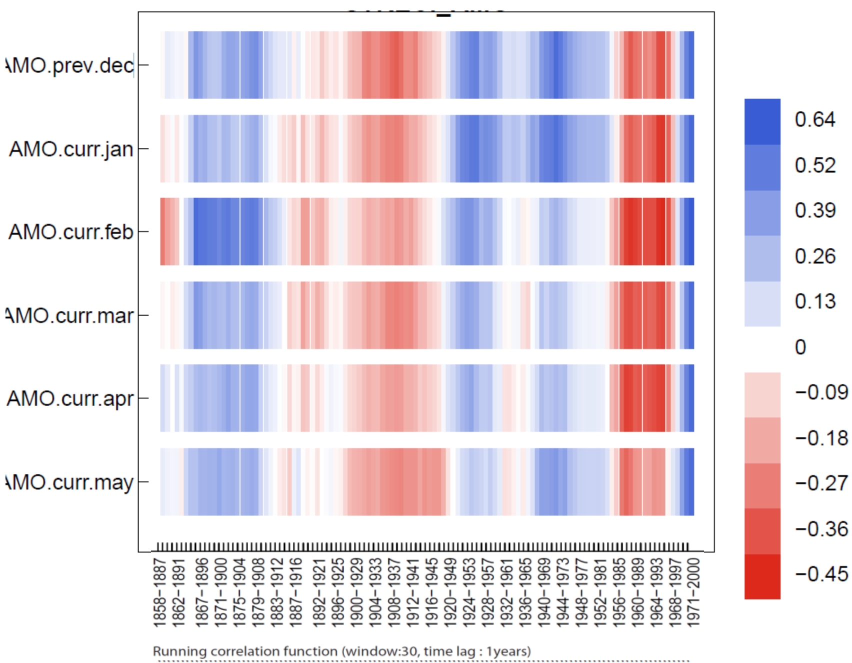

Figure I. Correlation coefficient between i-STREC and the AMO index (Enfield *et al.,* 2001), The positive correlations are in blue, the negative, in red

[1.4] The authors state that they do not train on the period of 1900-1929 due to the lack of weather stations within 300 km of their study area during that time. Was there a particular reason to choose 300 km and 1930 as the specific thresholds? Many authors have noted that temperature anomalies are correlated at distances exceeding 1000 km (Hansen and Lebedeff, 1987; Rohde et al., 2013; Cowtan and Way, 2014) therefore interpolation methods such as those employed in the CRU TS dataset should perform reasonably well in the absence of local station data.

A strong climate spatial variability was observed in the Labrador-Québec Peninsula in relation with contrasted atmospheric teleconnection influence (Nicault *et al.,* 2014). This variability seems to be even more important in the past. Moreover, as stated in the submitted paper, we obtained correlations between the regional series resulting from the data normalized for the three closest stations to our site (Schefferville, Wabush, Nitchequon; 1943-2010) and data from several remote stations that covered a period preceding 1943-2010. Data from many remote stations showed no significant correlations with the regional data. This observation allowed us to determine that any CRU data preceding 1930 should not be considered in the calibration period (1930-2010).

[1.5.1] The authors exclude the post-2000 data from calibration because of a divergence which they attribute to a change in growing season that affected the relationship between temperature and the S18 values. Would this change in growing season and the resultant non-linearity not be a concern for other decades of rapid warming throughout the record?

The comment suggesting the possibility of changes in growing season can have occurred in previous phases of the millennial record is valid. Inevitably, this sort of consideration referring to past changes in climatic regimes is always pertinent when discussing reconstructions of climatic parameters based on statistical models. This limitation is inherent to the calibration method which assumes that present conditions are warrant of the climatic past. The validity of the assumption could eventually be assessed by combining ecophysiological approaches with isotopic reconstruction.

[1.5.2] Similarly could there not be additional causes for the divergence which could be considered viable?

We are open to suggestions to explain the divergence after 2000 between tree-ring $\delta^{18}O$ values and JJA max T. Please note that we have evaluated the possible influence on $\delta^{18}O$ values of *el Niño*, snow cover changes, humidity changes, and hydric stress using available data. The only cause that coincided in time with the period of divergence and had the potential of explaining the isotopic departure in mechanistic terms was the observed change in the duration of the growing season.

[1.6] The authors state that the i-STREC values are representative of the natural variability of the region based on the relatively good correlation (r2=0.64) with the CRU TS series; however, the authors also note that both series were smoothed at 9-year intervals therefore it is expected that the strength of this relation may be somewhat overstated;

As shown in Naulier *et al.* (2014), the correlations obtained between tree-ring $\delta^{18}O$ values of living trees (sampled with an annual resolution) and standardized JJA maximal temperature are highly significant (r^2=0.25) even when using 4 trees (instead of 5 as in i-STREC) and including the divergent period. In other words if one were to use data not smoothed, the correlation would still allow to reconstruct Tmax. The r^2 obtained for the cohort series in the submitted paper is indeed excellent. One should consider that the methodological smoothing produced by the cohort strategy may increase the statistical link existing between Tmax and $\delta^{18}O$ values, but it does not create an artificial or false linkage.

[1.7] The authors state that a warm phase of the AMO could cause the warm period observed during the MWP but they also state that there was an overall decline in temperatures consistent with orbital cooling (reduced summer insolation). It would seem that there is little need in speculating as to the relationship with the AMO during that time period as there is not a clear understanding of the AMO state during the MWP. Sicre *et al* (2014) have argued that during the MWP there was enhanced Labrador Current activity which would seemingly argue against North Atlantic SSTs being the major driver of regional warming at that period.

It is a good point. We have now extended the text that was already referring to AMO in the discussion (lines 328-336): "In contrast, the AMO influences spring and summer temperatures (Fortin and Lamoureux, 2009) and is partly responsible for the recent sea surface temperature warming of northeastern Canada (Ding *et al.,* 2014). However, the state of the AMO at the beginning of the millennium being unknown, it is difficult to assess its influence on climate during the MWA. Recently, Sicre *et al*. (2014) have demonstrated that during the MWA, the strong Northern Annular Mode (NAM) was concomitant with a strong ice-loaded Labrador Current (LC). This combination could be responsible for a decrease of fresh air from Arctic to eastern Canada and consequently, for an increased temperature along the continent during a part of the medieval period."

[1.8] The authors note the difference between reconstructed MWP summer temperatures in their reconstruction and prior works which have found unprecedented warmth in recent decades relative to that period at the hemispheric scale. Here it is worth noting that this is not necessarily contradictory in that the reconstructions have different target seasons (annual versus summer). As anthropogenic warming at high latitudes has a strong winter signal relative to summer, it would not be unexpected that summer air temperature reconstructions may give different results than an annual average. According to Way and Viau (2014), winter air temperatures in the region have increased at a much faster rate than summer air temperatures therefore this point should be considered.

According to CRU TS 3.1 data for the studied region, Tmax of summer months has increased with an average of 1.2°C between 1940 and 2010 whereas winter temperature has not increased but shown the strongest variability in the studied region (Figure II). In other words, the winter trend discussed by Way and Viau is not recognized in our region. Additionally, knowing that the correlation between June to August Tmax and annual Tmax is strong (r^2=0.64), we can argue that our reconstructed summer Tmax can be representative of an annual Tmax.

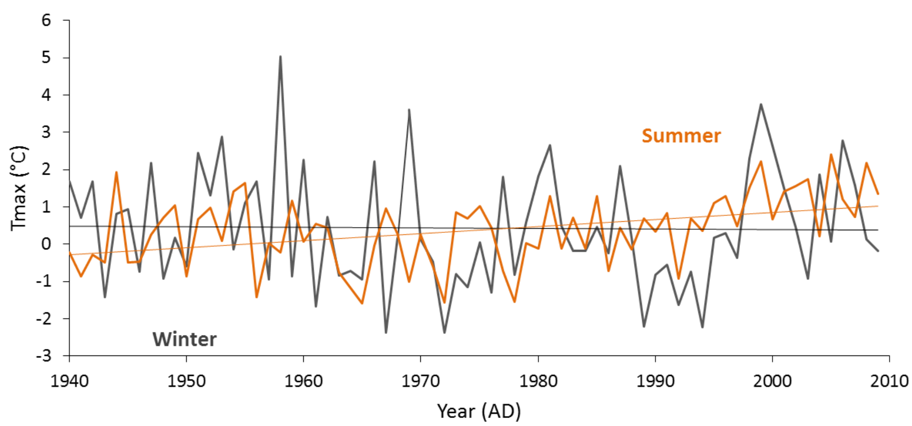

Figure II. Maximal temperature for summer (June to August; orange curve) and winter (December to February; grey curve) months and their linear regressions.

[1.9] In discussing the tree ring response to volcanic events it is worth discussing Tingley et al (2014) - particularly given the high latitude study area in question.

We now discuss this publication in the text addressing the record of solar radiations by trees in lines 398-401: "In addition, Tingley *et al*. (2014) have demonstrated, by analyzing the ring density in trees growing at high latitude, that the trees recorded not only volcanic eruptions but also variations in light intensity. This finding indicates that both isotopes and density of trees can record changes in solar radiations."

[1.10] Brown et al (2012) should also be mentioned in the text given that it also examines climate in this region.

We are convinced that this paper is of great interest for discussing climate of Nunavik and Nunatsiavut. However it is not so relevant for a discussion addressing northeastern Canada climate. Moreover, the study by Brown *et al*. covered only a part of the last century whereas we focused on a millennial reconstruction which permitted to identify the decadal and centennial climatic variability.

Comments from N. Loader (Referee)

Scientific Significance

[2.1] Does the manuscript represent a substantial contribution to scientific progress within the scope of Climate of the Past (substantial new concepts, ideas, methods, or data)? YES- new and novel data carefully compiled. A large amount of effort has been invested to produce this record which represents an important step in understanding the isotope and climate variability of this region.

Scientific Quality

[2.2.1] Are the scientific approaches and applied methods valid? Are the results discussed in an appropriate and balanced way (consideration of related work, including appropriate references)? Yes, the methods are appropriate for the dataset and significant background work has been conducted prior to completion of the long timeseries. Some detail on the signal strength during the calibration period might be helpful to gauge the suitability of the levels of replication.

We have added information on the calibration/verification results (lines 281-286): "However, it appears that the calibration coefficient and verification are changing according to the choice of the period. This fact can be explained by the fact that the correlation between maximal temperature and $\delta^{18}O$ series is not always stable during the last century even if the correlation stays significant."

[2.2.2] The join point plus off-set pooling approach used has been demonstrated to work, but without doubt sampling more longer-lived trees which cross cohorts would strengthen the lower frequency signal further still. Is there any evidence of a juvenile effect in the oxygen isotopes?

Black spruce trees are recognized for having lifespan generally shorter than 400 years. In our study, the living trees sampled did not exceeded 200 years. Considering in addition that (1) the boreal forest is known for having a high fire recurrence, and (2) the high rate of rejection during sampling due to strong wood degradation, it was extremely difficult to find longer-lived trees at the study site. Nevertheless, we think that using long-lived trees which cross cohorts could be a good approach for improving the correction robustness of cohort off-sets.

We know that a juvenile effect can exist with δ^2H (or $\delta^{18}O$) tree-ring series during the first twenty years of growth (Lipp *et al.,* 1993). In order to determine if this effect existed in black spruce trees from northeastern Canada, we sampled all tree rings of living trees and analyzed their $\delta^{18}O$ series individually. As can be seen on Figure III, we determined that there is no juvenile effect when oxygen isotopes are used in black spruce trees from northeastern Canada.

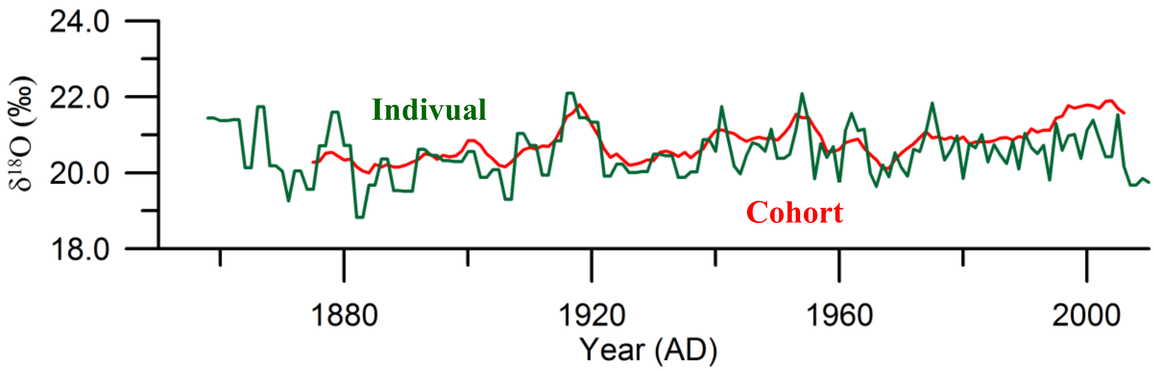

Figure III. The $\delta^{18}O$ series of 4 living trees sampled at an annual resolution (green curve) and for 5 trees sampled according to the cohort method (red curve).

[2.3.1] The interpretation of the record as temperature provides a general interpretation based upon the calibration period, however, and as the authors correctly state, oxygen isotopes are not a single instrumental temperature variable, but relate instead to circulation, hydroclimate, temperature etc. Interpretation as temperature may be more “accessible” but may only tell a part of the story. In this respect, I would personally be cautious in reporting differences in “temperature” during the past without a more detailed discussion of the isotope climate of the region, particularly when the recent past (last 5 years) do not closely calibrate (the decision not to calibrate with this truncated period could be misinterpreted so perhaps the full - period calibration could also be presented and reconstructed).

As stated by the referee, temperature is not the only climatic parameter controlling the oxygen isotopic fractionation in northeastern Québec. For that reason we had already attested for that fact in the discussion. It is worth noting that recent studies of living trees in the same region have already shown and discussed why summer temperature exerted the main control on the $\delta^{18}O$ variations (Naulier *et al.,* 2014, Bégin *et al.,* 2015). We suggest not repeating that discussion here. We have also verified that during the period of divergence, there is no other correlation with other parameters gaining in statistical strength (i.e., VPD, snow cover, humidity, precipitation). Concerning the presentation of the full-period calibration, it has been tested and unfortunately it leads to a much weaker statistical link (r^2=0.35) than when calibrating after removing the divergent period (r^2=0.64).

[2.3.2] However, that said, reporting this as a “divergence” in the dendroclimatological - sense may equally be misunderstood by some dendrochronologists/climatologists less familiar with the approach, since there is no evidence that the relationship in isotope fractionation has changed, just that the relationship between the isotopes sampled by the trees and summer temperature has changed. It may be possible to draw support for this hypothesis using local GNIP data. Alternatively, if the species is suitable for densitometry then there may be scope for a detrended reconstruction of temperature against which to compare the oxygen isotopes through time. Interpretation against solar variability is appropriately cautious.

Please read reply to comment 1.5.1 by M. Way concerning the divergence problem: “The comment suggesting the possibility of changes in growing season can have occurred in previous phases of the millennial record is valid. Inevitably, this sort of consideration referring to past changes in climatic regimes is always pertinent when discussing reconstructions of climatic parameters based on statistical models. This limitation is inherent to the calibration method which assumes that present conditions are warrant of the climatic past. The validity of the assumption could eventually be assessed by combining ecophysiological approaches with isotopic reconstruction."

The change in length of the growing season is a fact depicted by regional instrumental records. This change over the last decade, namely an extension of growth duration, from June-August to May-September is likely the cause of divergence, which was specifically operated through a change in source water isotopic ratio (Naulier *et al.,* in press). Unfortunately, this assumption cannot be reinforced by using GNIP data because at the L20 area, the $\delta^{18}O$ series of precipitation is only available for a very short period (1960-1969) which does not include the divergence period.
However, the option of using ring densitometry to obtain a detrended reconstruction of temperature to be compared with the $\delta^{18}O$ series is an excellent suggestion that should be applied in a new project.

Presentation Quality

[2.4] Are the scientific results and conclusions presented in a clear, concise, and well-structured way (number and quality of figures/tables, appropriate use of English language)? YES – the paper is clearly written and well written. Some axis labels require attention (maximale etc.) otherwise the figures are of good quality.

The mentioned problem was related to Figure 4 of the paper and it has been corrected.

Access Review, Peer - Review & Interactive Public Discussion (CPD)

In the full review and interactive discussion the referees and other interested members of the scientific community are asked to take into account all of the following aspects:

[2.5] Does the paper address relevant scientific questions within the scope of CP? YES

[2.6] Does the paper present novel concepts, ideas, tools, or data? YES – new data for the region; a terrestrial isotope record.

[2.7] Are substantial conclusions reached? Isotope climatology is at an early - stage, but appropriate conclusions are drawn.

[2.8] Are the scientific methods and assumptions valid and clearly outlined? This work has been VERY carefully conducted and thoughtfully compiled. Important background work has been conducted over many years. The join-point approach seems to work well here, but additional replication at both join-points and within the body of the reconstruction would undoubtedly strengthen the record, as would incorporation of longer-lived trees. Interpretation as temperature is only part of the "isotope story". The truncated calibration should be addressed in more detail here.

Indeed, additional replication at both join-points and points within the body of the reconstruction would undoubtedly strengthen the record: in statistical reconstruction procedures, the higher is the number of samples; the more robust is the reconstruction. However, we assure the referee that we have made hard and long work in order to obtain the maximum number of these lake-extracted subfossil trees for the reconstruction, having had to discard trees with short lifespan, rings too small for mechanical sampling or with textural degradation. After this sorting, cohorts of 5 trees per years were available to cover the entire millennium, and between 10 and 25 trees for join points were available. The region investigated is far and isolated, the option of increasing these numbers would require substantial research funds and demanding logistics, but in the end, we do not think it would change the main conclusions presented in the article.

[2.9] Are the results sufficient to support the interpretations and conclusions? Yes, within the limits of the calibration as presented.

We have explained why the calibration period is reducing to 1930-2000 in the methodology section. Please note that the divergence problem is the specific subject of Naulier *et al*., in press).

[2.10] Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)? Although some elements of the methods are brief. The cited papers identify the many elements of this work have been evaluated by the team elsewhere, so this information is available I believe. I could not see/access supplementary data (see note below) so it was not possible to attempt to recalculate.

In the methodology section, we present briefly the main steps of the method because the sampling strategy is well explained in Gagen *et al.,* 2012. However, the changes made to the approach are discussed in details both in the methodology and the discussion. Additionally, all isotopic results are available on-line in Naulier, 2015 (Ph.D. thesis).

[2.11]. Do the authors give proper credit to related work and clearly indicate their own new/original contribution? Yes

[2.12]. Does the title clearly reflect the contents of the paper? Yes.

[2.13]. Does the abstract provide a concise and complete summary? Yes.

[2.14]. Is the overall presentation well-structured and clear? Yes.

[2.15]. Is the language fluent and precise? Yes.

[2.16]. Are mathematical formulae, symbols, abbreviations, and units correctly defined and used? Yes.

[2.17]. Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated? See review notes.

[2.18]. Are the number and quality of references appropriate? Yes.

[2.19]. Is the amount and quality of supplementary material appropriate? I was not able to access /see a link to any supplementary data – but as a minimum the raw and join point corrected data should be presented versus calendar age in addition to the final reconstruction.

We have added the reference to the Ph.D. thesis of the first author (Naulier, 2015) that is available online. Any interested scientists can access the tables presenting all results, $\delta^{18}O$ values of join points and cohorts before and after their adjustments, etc. The supplementary material presented (Table I, II and III) completes the database with information on lifespan of trees and sampled periods and i-STREC data.

Comments of H. Linderholm (Referee)

Scientific significance

[3.1.1] This is clearly an exciting new record, adding to the few millennium long isotope series that are currently emerging. It is a nicely written manuscript using an excellent dataset. Still, I would have liked to see a more critical discussion of the method (see below) as well as using isotope data from subfossil wood in terms of temporal stability of the signal (something I have thought about quite a lot regarding the data we collect in Sweden). As an example, it is stated that the last decade of data is not used due to changes in the growing season, but maybe also the "MWA" was a period of increased/changed growing season? See also my comment below regarding fluctuations of lake levels.

This comment suggests the same reply as to comment 1.5.1: "The comment suggesting the possibility of changes in growing season can have occurred in previous phases of the millennial record is valid. Inevitably, this sort of consideration referring to past changes in climatic regimes is always pertinent when discussing reconstructions of climatic parameters based on statistical models. This limitation is inherent to the calibration method which assumes that present conditions are warrant of the climatic past. The validity of the assumption could eventually be assessed by combining ecophysiological approaches with isotopic reconstructions".

[3.1.2] Also, it is interesting of course to compare a new record to others to see how it "performs", but I feel that this new record warrants a deeper discussion of its pros and cons.

We have added new information about the pros and cons of the sampling method on lines 257-266. "Although the cohort sampling method has shown many positive points, it is nevertheless important to highlight some concerns about this procedure. Indeed, the sampling strategy produces a $\delta^{18}O$ series smoothed with a centered 9-years filter. This smooting leads in some cases to series requiring more care than non-smoothed series before they can be interpreted or used. For instance, the calibration of our smoothed $\delta^{18}O$ series required a centered 9-years filtering of the climatic series. Consequently, correlations between isotopic and climatic series are generally overestimated. It is important to highlight that even if the correlations are improved by smoothing due to the sampling method; they nevertheless represent a solid and real link, and do not create an artefact (see also the discussion on the calibration/verification method of next section, Naulier *et al.,* 2014)."

Scientific quality

[3.2] The (cohort) method has been tested before, but personally I feel that the approach, where there is only a slight overlap between to neighbouring (short) cohorts, can possibly introduce some bias, which should be discussed.

The slight overlap between cohorts does not introduce bias because, as written in the paper, "the $\delta^{18}O$ values of intersection points between two successive cohorts and JP $\delta^{18}O$ means are surprisingly matching in nine cases out of eleven" (Figure 3A). These observations are expressing a robust coherence of the sub-populations of stems that were sampled in lake L20 of northeastern Canada.

[3.3.1] Could the age of the trees as well as a possible disintegration of the sapwood cause any impact on the results?

As written in the methodology section, we have removed all trees that presented textural degradation and subsequently assessed the integrity of the isotopic ratios in subfossil cellulose by comparing it with lignin values in modern living trees and in modern and very old subfossil trees. In addition, as shown in Figure IV, we have addressed the issue of using subfossil trees and of the reliability of their isotopic ratios. Indeed, as written in our article, we have used the textural pre-selection of wood combined with verifying the coherence of the cellulose isotopic values as proposed by Savard *et al.* (2012). This practical step consists in calculating the cellulose-lignin $\Delta\delta^{18}O$ values (subtracting the lignin $\delta^{18}O$ values from the cellulose values). This isotopic difference was calculated for the 1890 to 1905 period during which the subfossil and living series are overlapping, and for two contrasted climatic periods of the subfossil record: 1145-1160 and 1745-1760.

These $\Delta\delta^{18}O$lignin-cellulose values in living trees vary between 12.8 and 15.4‰ (Figure B, D), matching the variability found for subfossil stems (1890-1905; D) and others that grew up under different climatic conditions (1145-1160 (B) and 1745-1760 (C)). This approach allowed assessing the integrity of the isotopic results over the last millennium.

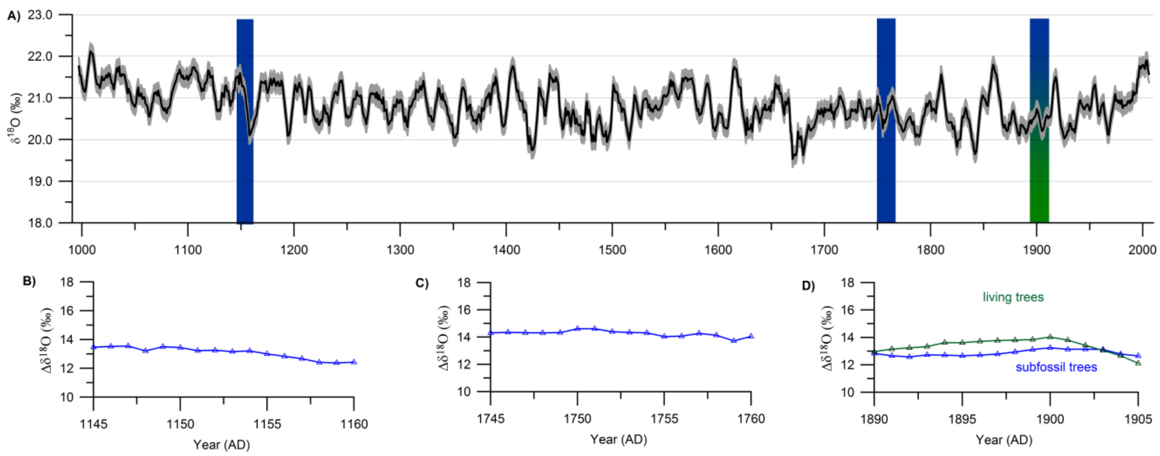

Figure IV. (A) Millennial $\delta^{18}O$ series with box corresponding to the period where $\Delta\delta^{18}O$ values have been calculated. The calculated $\Delta\delta^{18}O$ values for the (B) 1145-1160, (C) 1745-1760, and (D) 1890-1905 periods. Results for subfossil stem values are in blue and for living trees, in green.

Concerning the age of trees and the potential juvenile effect, we invite the referee to read the answer to comment 2.2.2 by N. Loader, which explains why we consider that the studied black spruce trees do not show juvenile effect in $\delta^{18}O$ series: "We know that a juvenile effect can exist with δ^2H (or $\delta^{18}O$) tree-ring series during the first twenty years of growth (Lipp *et al.,* 1993). In order to determine if this effect existed in black spruce trees from northeastern Canada, we sampled all tree rings of living trees and analyzed their $\delta^{18}O$ series individually. As can be seen on Figure III, we determined that there is no juvenile effect when oxygen isotopes are used in black spruce trees from northeastern Canada."

[3.3.2] Were some trees included in more than one cohort?

Not at all, every tree is used only once. Please see the now added supplementary material (Table I and II), where the lifespan of trees and tree rings sampled for constructing each cohort are all identified.

[3.3.3] Also, it is clear from the calibration/verification exercise that the strength of the Tmax signal differs between the periods (e.g. RE and CE values). I think that the impact of this manuscript would improve a lot if the data and methods were addressed a bit more thoroughly.

We have added explanations about why the signal differs between the periods on lines 281-286: "However, it appears that the calibration and verification coefficients are significantly changing depending on the period selected for the statistical analysis. This observation implies that the correlation between Tmax and δ^{18}O series is not stable over the last century even if the correlation stays significant (Naulier *et al*. in press)."

Presentation quality

[3.4.1] The presentation of the data is OK, but slightly more information on the trees used in the study would be beneficial, as well as the methods used.

Please see the reply to comment [3.3.3].

[3.4.2] However, I feel that too much text is spent on trying to link the i-STREC to pervious reconstructions and find potential forcings of the observed long-term variability. I would have liked to see a more detailed discussion about the potential impacts of using isotopes from lakeshore trees as temperature indicators (where it has been suggested that fluctuating lake levels can affect the temperature sensitivity), or if the isotope values may be affected by being submerged.

Please see reply to comment of R. Way (1.1) where he suggests that the paragraph comparing i-STREC to other reconstructions need to be longer. According to comments from reviewer Way and knowing that the comparison with other series is used to invoke climate-driving mechanisms, we are led to think that the length of the paragraph is appropriate.

The impact of lake level variations on δ^{18}O series of riparian trees has already been assessed in Naulier *et al.,* in press. In this article, we have compared δ^{18}O series of riparian trees sampled at L20 with δ^{18}O series of trees sampled at a nearby mesic site (HM1). We have found that series from HM1 and L20 were strongly correlated (r=0.88) and showed similar variations. This observation indicates that level fluctuations of the lake do not affect the δ^{18}O series of riparian trees at the study site.

[3.4.3] Also, I would have liked to see the corresponding TRW chronology (based on the same "cohort" method) from this particular lake to compare with the isotope chronology. It is clear that they differ and the discussion of this could be more informative.

Agreed. However, obtaining and comparing the δ^{18}O series with a TRW series obtained using the same cohort approach is a colossal task that could be the subject of another article. We would like to remind the referee that our main objective here was to reconstruct the last millennium in northeastern Canada by using isotopes, not ring width series as already used by Gennaretti *et al.* (2014). In addition, the TRW information corresponding to trees used for i-STREC are all reported in the supplementary material of Gennaretti *et al.* (2014). Concerning the comparison of TRW and δ^{18}O series for our study site, we did it and we discussed the differences between them in a long paragraph of the discussion, underlining that even if the signals extracted from the two series sometimes diverge due to differences between processes influencing isotopic assimilation and ring-width growth, the two signals give complementary information of the past climate in northeastern Canada (lines 402 to 441). Finally, we think that applying the cohort approach to TRW series is not adequate as climatic reconstruction using this proxy is not limited in terms of number of samples or analytical costs, two constraints that unfortunately exist when working with isotopic series.

Access review, peer review, and interactive public discussion (CPD)

[3.5] Does the paper address relevant scientific questions within the scope of CP? Yes.

[3.6] Does the paper present novel concepts, ideas, tools, or data? Yes, but could be improved with some critical discussion of the data and methods.

We have added new points about pros and cons of the method on lines 257-266: "Although the cohort sampling method has shown many positive points, it is nevertheless important to highlight some concerns about this procedure. Indeed, the sampling strategy produces a $\delta^{18}O$ series smoothed with a centered 9-years filter. This smooting leads in some cases to series requiring more care than non-smoothed series before they can be interpreted or used. For instance, the calibration of our smoothed $\delta^{18}O$ series required a centered 9-years filtering of the climatic series. Consequently, correlations between isotopic and climatic series are generally overestimated. It is important to highlight that even if the correlations are improved by smoothing due to the sampling method; they nevertheless represent a solid and real link, and do not create an artefact (see also the discussion on the calibration/verification method of next section, Naulier *et al.,* 2014)."

.

[3.7] Are substantial conclusions reached? Yes, although a slightly more critical discussion would be beneficial, and may change the conclusions. Also, I'm not fully convinced by the presented figures that solar forcing is the most important forcing.

In the paper, we showed that several solar minima (more than the half) coincided with periods of minimal temperature in northeastern Canada. We are aware that the solar forcing is not the only forcing that played along to regulate climate in the study region. However, at this stage, the solar radiations appear as being the main climatic forcing that may have dominated during the inferred periods of minimal temperature. All the other forcings that we have examined did not show matching periods with temperature extremes (NAO, AMO, El-Nino, volcanic eruptions…). In simple terms, here we present solar forcing to control temperature lows in northeastern Canada as a possible interpretation, which in the case of the period of low T of the 19th century is combined with volcanic activities. Clearly, we do not discard the possibility that other forcings have exerted key roles during the last millennium.

[3.8] Are the scientific methods and assumptions valid and clearly outlined? OK.

[3.10] Are the results sufficient to support the interpretations and conclusions? Would likely change somewhat after revision.

[3.11] Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)? I'm not fully convinced by the cohort method because of the limited overlap between them, however, this may be clearer if also the time spans of the samples are shown (since I guess that one tree can contribute to several cohorts?).

Please see replies to comments [2.8] by N. Loader and [3.3.2] for these points. Figure 2 illustrates the time-span covered by every investigated tree. Of course the life span of trees was longer than the part sampled for the reconstruction, because the method requires using 5 stems overlapping in time, i.e. removing rings that are not necessary for producing the millennial isotopic series. The reader is referred to the supplementary material (Table I and II) where all years covered by dated rings in subfossil stems are reported.

[3.11.2] Also, I feel that the discussion of the influence of the AMO (and lack of NAO) is a bit speculative.

The discussion about the possible AMO control is based on other papers addressing that question for northern Canada. However, we are aware that based on the knowledge of the AMO state during the MWA, its potential impact on summer temperature in the study region is only an assumption. According to comment 1.7 by R. Way, we now discuss the potential influence of the Labrador current on temperature of the L20 region over the last millennium (lines 328-336 of the manuscript): "In contrast, the AMO influences spring and summer temperatures (Fortin and Lamoureux, 2009) and is partly responsible for the recent sea surface temperature warming of northeastern Canada (Ding *et al.,* 2014). However, the state of the AMO at the beginning of the millennium being unknown, it is difficult to assess its influence on climate during the MWA. Recently, Sicre *et al*. (2014) have demonstrated that during the MWA, the strong Northern Annular Mode (NAM) was concomitant with a strong ice-loaded Labrador Current (LC). This combination could be responsible for a decrease of fresh air from Arctic to eastern Canada and consequently, for an increased temperature along the continent during a part of the medieval period."

[3.12] Do the authors give proper credit to related work and clearly indicate their own new/original contribution? Yes.

[3.13] Does the title clearly reflect the contents of the paper? Yes

[3.14] Does the abstract provide a concise and complete summary? OK (but why the Medieval Warm Anomaly??? MWP or MCA).

We are using MWA all along the text as used by several authors (e.g., Trouet *et al.,* 2009; Mann *et al.,* 2009). But is it clear that MWP is also a largely accepted appellation in the literature.

[3.15] Is the overall presentation well-structured and clear? Yes.

[3.16] Is the language fluent and precise? Yes.

[3.17] Are mathematical formulae, symbols, abbreviations, and units correctly defined and used? Yes.

[3.18] Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated? See previous comments

[3.19] Are the number and quality of references appropriate? Yes.

[3.20] Is the amount and quality of supplementary material appropriate? NA.

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<u>Changes in the manuscript</u> (note that changes added to the previous paper are only additional information and not a modification of the previous content).

- Lines 257 to 266
- Lines 281 to 286
- Lines 328 to 336
- Lines 360 to 370

A millennial summer temperature reconstruction for northeastern Canada using oxygen isotopes in subfossil trees

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Abstract

Climatic reconstructions for north-eastern Canada are scarce such that this area is under-represented in global temperature reconstructions. To fill this lack of knowledge and identify the most important processes influencing climate variability, this study presents the first summer temperature reconstruction for eastern Canada based on a millennial oxygen isotopic series ($\delta^{18}O$) from tree rings. For this purpose, we selected 230 well-preserved subfossil stems from the bottom of a boreal lake and five living trees on the lakeshore. The sampling method permitted an annually resolved $\delta^{18}O$ series with a replication of five trees per year. The June to August maximal temperature of the last millennium has been reconstructed using the statistical relation between Climatic Research Unit (CRU TS3.1) and $\delta^{18}O$ data. The resulting millennial series is marked by the well-defined Medieval Warm Anomaly (MWA; AD 1000-1250), the Little Ice Age (AD 1450-1880) and the modern period (AD 1950-2010), and an overall average cooling trend of -0.6°C/millennium. These climatic periods and climatic low frequency trends are in agreement with the only reconstruction available for northeastern Canada and others from nearby regions (Arctic, Baffin Bay) as well as some remote regions like the Canadian Rockies or Fennoscandia. Our temperature reconstruction clearly indicates that the Medieval Warm Anomaly has been warmer than the modern period, which is relatively cold in the context of the last 1000 years. However, the temperature increase during the last three decades is one of the fastest warming observed over the last millennium (+1.9°C between 1970-2000). An additional key finding of this research is that the coldest episodes mainly coincide with low solar activities and the extremely cold period of the early 19th century has occurred when a solar minimum was in phase with successive intense volcanic eruptions. Our study provides a new perspective unraveling key mechanisms that controlled the past climate shifts in northeastern Canada.

1. Introduction

The recently published work of the Intergovernmental Panel on Climate Change (IPCC AR5, 2013; PAGES 2K consortium, 2013) has shown that north-eastern Canada is poorly represented among existing millennial temperature reconstructions in the northern hemisphere. For this reason, a better knowledge of regional past climate variations registered in natural archives is needed. The use of natural archives such as trees, sediment or pollen has permitted the reconstruction of temperature variability at regional, hemispheric and global scales for the past millennium (Hegerl *et al.,* 2007; Mann *et al.,* 2009; Moberg *et al.,* 2005; PAGES 2k consortium, 2013). Although some studies have documented past climatic conditions in northern Canada (Moore *et al.,* 2001; Thomas and Briner, 2009; Luckman and Wilson, 2005; Edwards *et al.,* 2008; Viau and Gajewski, 2009; Gajewski and Atkinson, 2003), only one annually-resolved millennial temperature reconstruction based on tree-ring widths exists for eastern Canada (Gennaretti *et al.,* 2014; summer temperature reconstruction for Eastern Canada, STREC), but none has been based on the isotopic approach. Consequently, obtaining millennial-long, high-resolution temperature reconstructions from additional proxies in north-eastern Canada is important to increase our knowledge of the past climate, and better understand the mechanisms of climate change.

Tree-ring isotope series present the advantage that they generally do not need to be detrended; they retain climatic low frequency variations, and require fewer trees compared to classical dendrological methods (Loader *et al.,* 2013; Robertson *et al.,* 1997; Young *et al.,* 2010). Moreover, oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) series have proven their suitability for reconstructing past summer temperatures (Porter *et al.,* 2013; Luckman and Wilson, 2005; Barber *et al.,* 2004; Anchukaitis *et al.,* 2012). Whereas $\delta^{13}C$ series have often been used for long climatic reconstructions, only a few studies have used long $\delta^{18}O$ series (Edwards *et al.,* 2008; Richter *et al.,* 2008; Treydte *et al.,* 2006; Wang *et al.,* 2013). A previous study has already proven that $\delta^{18}O$ is the most suitable isotopic proxy for summer temperature reconstruction in our study region (Naulier *et al.,* 2014; Naulier *et al.,* in press).

In northern Canada, most tree species rarely live more than 300 years (Arseneault *et al.,* 2013). In such regions where old trees are missing, isotopic chronologies can be extended by combining living specimens with subfossil trees preserved in lakes (Boettger *et al.,* 2003;

Gagen *et al.,* 2012; Mayr *et al.,* 2003; Savard *et al.,* 2012), and cross-dating stems to determine subfossil tree ages (Arseneault *et al.,* 2013). For the purpose of paleoclimate studies, subfossil stems can be easily extracted and collected from large stocks of drowned subfossil logs in lakes and can be associated with specific edaphic contexts as most specimens are not redistributed in lakes (Gennaretti *et al.,* 2014a).

After cross-dating, the development of a robust millennial, isotopic chronology from the combination of living and subfossil stems involves replicating specimens in order to retain the climate variability of the study site (Haupt *et al.,* 2014; Loader *et al.,* 2013a). However, the amount of material available is often a constraint because of the short lifespans of trees, the difficulty to separate single and thin rings and obtaining enough cellulose for isotopic analysis (Loader *et al.,* 2013b; Boettger and Friedrich, 2009). To overcome these problems, different pooling methods have been developed such as inter-tree pooling (McCarroll and Loader, 2004; Dorado Liñán *et al.,* 2011), serial pooling of consecutive tree rings within an individual tree (Boettger and Friedrich, 2009), and the “offset-pool plus join-point method” (Gagen *et al.,* 2012). This last method has permitted constructing a millennial $\delta^{13}C$ series with annual resolution and high replication, while reducing the sampling efforts and laboratory analyses (Gagen *et al.,* 2012). Moreover, a statistical analysis of this method has confirmed its robustness and possible application for the production of millennial $\delta^{18}O$ series (Haupt *et al.,* 2014).

The present study aims to produce a new paleoclimatic data set based on tree-ring $\delta^{18}O$ series covering the last millennium in northeastern North America. For this purpose, we develop a 1010-years long $\delta^{18}O$ series using a combination of living trees and submerged subfossil stems from one site, and reconstruct the summer maximal temperature. We analyze the main characteristics of the climatic series and evaluate its robustness by comparison with other reconstructed temperature series. Finally, we explore the potential impact of natural forcing (solar radiation and volcanic eruptions) on past climatic variability in north-eastern Canada.

2. **Materials and methods**

2.1. **Study area**

The study site is located at the center of the Quebec-Labrador peninsula in north-eastern Canada (Figure1A). This area is part of the Precambrian Canadian Shield, mainly constituted of granitic and gneissic rocks. The landscape is characterized by a low altitude plateau (400-600 m), with abundant lakes and wetlands (Dyke *et al.,* 1989). Forests of the area are dominated by black spruce (*Picea mariana* (Mill.) BSP) trees, developed as pure open lichen woodlands on well-drained sites, and spruce-moss woodlands in depressions. Balsam fir (*Abies balsamea* (L.) Mill.) and Tamarack (*Larix laricina* (Du Roi) Koch) also grow in this region. Wildfires are the most important natural disturbances with a rotation period estimated between 250 to 500 years (Boulanger *et al.,* 2012).

The climate is continental and subarctic with short, mild summers and long, cold winters. Environment Canada data (Schefferville station) show that the 1949 to 2010 mean monthly temperature is -22.9°C in January and 13.3°C in July with a mean annual temperature of -3.9°C. Total annual precipitation averaged 640 mm with up to 60% falling in summer (June to September). The mean duration of the frost-free period is 75 days from mid-late June to mid-September. The lakes are generally frozen from mid-October to early June.

The selected lake (L20; 54°56'31'' N; 71°24'10'' W) is part of the large network of lakes sampled by our group (Arseneault *et al.,* 2013; Gennaretti *et al.,* 2014a and b). Ecological and morphological criteria have been developed to identify lakes that present the best potential for millennial-long climatic reconstructions (well-preserved subfossil trees) and large stocks of subfossil logs. These lakes are typified by an abrupt lake/forest transition, as well as log accumulation in the lower littoral zone away from ice erosion and waves (Arseneault *et al.,* 2013, Gennaretti *et al.,* 2014a, Gennaretti *et al.,* 2014c). Lake L20 has an altitude of 483 m and an area of 35.1 ha. It is bordered by open spruce-moss with lichen woodlands growing on well-drained podzolic soil and regular slope. The last severe wildfire occurred at about AD 1590 along the southern section of the studied shore segment and more than 1200 years ago along the northern section (Gennaretti *et al.,* 2014c).

2.2. Tree stem selection and sampling strategy

We recently demonstrated that isotopic series from different heights along lakeshore trees provide similar isotopic trends, and indicated that the combination of lakeshore black spruce trees with subfossil stem segments does not introduce artefacts in long $\delta^{18}O$ series, thus permitting their combination for climatic reconstruction (Naulier *et al.,* 2014). In the present study, subfossil stems were selected from a large collection of 586 cross-dated specimens from lake L20, also used in the STREC reconstruction (Gennaretti *et al.,*2014b), based on their excellent degree of preservation (Savard *et al.,* 2012), relatively large ring width (>0.2 mm) and their life span (Supplementary material, Table I). The development of a millennial isotopic series requires choosing an appropriate method to preserve both high and low climate frequencies, while limiting analytical efforts. We decided to adapt the “offset-pool plus join-point method” (Gagen *et al.,* 2012) in order to obtain an annual resolution with a replication of five trees for each year.

According to this sampling method, one cohort is made by selecting segments from five contemporaneous trees such that each cohort overlaps the next one over five years. In our case, five living trees were selected to construct a modern cohort (CV; AD 1860-2006) and 60 well-preserved subfossil stems from the lake floor were used to produce 12 subfossil cohorts (C0 to C11; AD 997-1956; Figure 2). Overall, our cohorts cover between 59 and 111-years and the complete suite of cohorts extends from AD 997 to 2006. Additionally, within every cohort, each tree was divided into five-year blocks which were offset by one year among trees (Supplementary material, Table II). As a consequence, the $\delta^{18}O$ value obtained for a specific year is the mean of the isotopic results from five trees, which represents a triangular centralized nine-year moving average.

2.3. **Laboratory treatment**

We extracted α-cellulose sub-samples according to a standard protocol modified for small samples at the Delta-lab of the Geological Survey of Canada (Green, 1963; Savard *et al.,* 2012). The extracted α-cellulose was dried at 55°C for 12 hours and sub-samples analyzed using peripherals on-line with gas-source isotope ratio mass spectrometers (IRMS). All material was analyzed for $\delta^{18}O$ values with a pyrolysis-CF-IRMS (Delta plus XL). The analytical accuracy of this instrument was 0.2‰ (1σ), as established by using international standards (IAEA-SO-6 and IAEA-NBS-127). All $\delta^{18}O$ measures are reported in permil (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW). A total of 2192 analyses were produced, with, in addition, 24% of all samples retreated and analyzed to determine the external precision (reproducibility) of the complete procedure (0.2‰, 1σ).

2.4. Cohort corrections and climatic reconstruction

When a long isotopic series is produced from trees coming from a random assemblage, joining two successive cohorts may be difficult due to the existence of isotopic offsets between cohorts. An approach to overcome this problem is to use the mean of $\delta^{18}O$ values coming from several tree segments from the overlap period between two successive cohorts which permits to estimate a correction factor for the offset (Gagen *et al.,* 2012). In the present study, the construction of the millennial $\delta^{18}O$ series required such an adjustment for some cohorts. We have adopted the “join-point method” proposed by Gagen *et al.* (2012). A join-point (hereafter JP), corresponds to the mean results of 5-years blocks from several trees overlapping between two cohorts. We have used all available dated trees (between 10 and 24) to produce the required join points (JP 0 to JP 11), and verified several methods to correct for the offsets between cohorts. Hence, every cohort has been corrected by adding the linear regression calculated between the $\delta^{18}O$ values of its two ends.

The integrity of the isotopic signal has been verified elsewhere (Naulier, 2015). The $\delta^{18}O$ values of lignin and cellulose have been analyzed for three contrasted climatic periods of the millennium (AD. 1141-1164, 1741-1761 and 1886-1909), as detected in previous studies (e.g. Savard *et al.,* 2012). The cellulose isotopic integrity of the subfossil stems has been confirmed by the similarity of the Δ values between living trees and subfossil stems for the 1886-1909 period. In addition, the departure between the $\delta^{18}O$ values of lignin and cellulose ($\Delta=\delta^{18}O_{cellulose}-\delta^{18}O_{lignin}$) exhibit no temporal trend.

In previous studies, we have analyzed the relationships between $\delta^{18}O$ series of five living trees and various climatic parameters (temperature, precipitation, vapor pressure deficit, etc). We have established that $\delta^{18}O$ series of black spruce stems sampled at an annual resolution from boreal lakeshore were significantly correlated with June-August (JJA) maximal temperature (Tmax; r=0.54). We have also determined by statistical analysis (Buishand test, Buishand, 1982) that the summers became warmer after 1975 and that the growing season duration and degree-days have increased importantly during the last decade (2000-2010). Moreover, we have demonstrated that during this decade the growing season started sooner and finished later than before, changing the relationship between JJA maximal temperature and $\delta^{18}O$ series (divergence). In other words, this JJA Tmax and $\delta^{18}O$ series relation is stable and strong between 1930 and 2000(r_{mean}= 0.54; 1930-2000), but not after (AD 2000-2010; Naulier *et al.,* 2014; Naulier *et al.,* in press). Therefore, in the present study, we excluded the last decade (divergent years) when calibrating the $\delta^{18}O$ series on temperature data which is assumed to be non-representative of the temperature variation over the last century. The $\delta^{18}O$ series of subfossil cohorts are filtered on 9 years; we have made the choice to pass a 9-years centered-filter on the JJA maximal temperature CRU TS 3.1 in order to use series all treated in the same way for the reconstruction.

In a first step, a simple linear regression and a linear-scaling model were calibrated over the entire 1930-2000 period with climatic data. Climate data from the 1900-1929 period were excluded because no meteorological station was then operating at less than 300 km from the study site. The climatic series was separated into two equal periods (AD 1930-1970 and 1971-2000; Table 1) in order to test the robustness of the two calibration models, using the non-first-differenced reduction of error (RE), the coefficient of error (CE), the raw mean squared error (RMSE) and the coefficient of determination (r^2). The linear regression and the linear-scaling calibration procedures resulted in somewhat different temperature reconstructions of similar robustness with similar RE, CE, r^2 and RMSE coefficients. In both cases, the model residuals satisfy the standard linear regression assumptions of normality, variance and autocorrelation (not shown), but cannot reproduce all attributes of the measured data. We therefore tested the possibility of averaging the two model results, and this option gave the best reproduction of the measured Tmax. Consequently, we averaged results from the two reconstructions in order to obtain one robust reconstruction (Table 1; Supplementary material, Table III).

Then, i-STREC was compared to the only other regional temperature reconstruction (STREC; Gennaretti *et al.,* 2014), which is built from ring width data from 6 lakes, including our site, and with reconstructions based on tree rings from another boreal region (Fennoscandia, Helama *et al.,* 2002; Figure). We also compared i-STREC with independent temperature reconstructions based on other natural archives from North America and the Arctic region (Thomas and Briner, 2009; Kobashi *et al.,* 2011; Luckman and Wilson, 2005; Vinther *et al.,* 2009, Figure 5). Most published reconstructions are based on mean temperatures, except our reconstruction and the one from the Canadian Rockies, which are based on summer maximal temperatures. The influence of climatic forcings was evaluated through the comparison of i-STREC with time series of sulfate emission from volcanic origin (Crowley *et al.,* 2012) and solar radiation series (Bard *et al.,* 2003; Figure 6). The durations of the solar minima have been determined according to existing estimations of solar radiation (e.g., Bard *et al.,* 2003).

3. **Results and discussion**

3.1. **Development of $\delta^{18}O$ chronology**

As the purpose of the reconstruction was to identify contrasted periods and important temperature changes over the last millennium, the choice of the sampling method proposed by Boettger *et al.* (2009) was relevant because it allows for reconstruction of climatic parameters at an annual resolution with a replication of five trees per year. The range of $\delta^{18}O$ values of trees is between 19.5 and 22.0‰, and the largest $\delta^{18}O$ differences among trees within a junction is obtained for JP5 (3.8‰; Figure 3A). This large inter-tree variability can be explained by a combination of causes, including various growing locations along the lakeshore which influence their water supply (Figure 1B), and inter-tree metabolic variability (0.5‰ in Naulier *et al.,* 2014). Such variability confirms the need to take a large number of trees for a millennial reconstruction in order to capture the site signal (Loader *et al.,* 2013a).

The $\delta^{18}O$ values at intersections between two successive cohorts and of the JP $\delta^{18}O$ means are surprisingly matching in most cases (except at the C8/C9 and C3/C4 junctions; figure 3). These observations suggest that offset correction between cohorts is not always necessary. However, we have determined that a modification of the JP adjustment procedure published by Gagen *et al.* (2012) would optimize the correction while conserving the isotopic variability and trends over the millennium (Naulier, 2015). Hence, we have used the mean of

$\delta^{18}O$ values of JP from overlapping cohorts to calculate the required adjustment, this mean being considered as “the adjustment value”. Correcting cohort $\delta^{18}O$ series with this method increases the number of trees considered (20 to 33 trees instead of 10 to 23 trees if only JP are used). After correction, the mean of the millennial $\delta^{18}O$ series is 20.8‰. The strong correlation between the $\delta^{18}O$ series of living trees and subfossil stems (r^2=0.70) over their overlapping period (1860-1956) confirms the isotopic integrity of the subfossil stems, and ensures that the climatic reconstruction can be performed over the rest of the millennial $\delta^{18}O$ series.

Although the cohort sampling method has shown many positive points, it is nevertheless important to highlight some concerns about this procedure. Indeed, the sampling strategy produces a $\delta^{18}O$ series smoothed with a centered 9-years filter. This smooting leads in some cases to series requiring more care than non-smoothed series before they can be interpreted or used. For instance, the calibration of our smoothed $\delta^{18}O$ series required a centered 9-years filtering of the climatic series. Consequently, correlations between isotopic and climatic series are generally overestimated. It is important to highlight that even if the correlations are improved by smoothing due to the sampling method; they nevertheless represent a solid and real link, and do not create an artefact (see also the discussion on the calibration/verification method of next section, Naulier *et al.,* 2014).

Commentaire [NM1]: Information added

3.2. Model validation and millennial climatic reconstruction

3.2.1. Model validation

We have compared two methods of sampling and production of the ring series from living trees prior to calibration: (1) separation at an annual resolution without pooling (e.g., Haupt *et al.,* 2013); and (2) sampling with the cohort approach. We have found that the second was best suited because it slightly improved the correlation between $\delta^{18}O$ series and maximal temperatures (r^2=0.64 vs 0.54 with annual resolution), and it allows using $\delta^{18}O$ series compatible with the one used for the millennial subfossil series (9-years moving average). Consequently, the $\delta^{18}O$ series of the living-tree cohort (CV) was used to calibrate the model and to provide a robust reconstruction as it show a strong correlation with the new CRU series (r^2=0.64) for the entire calibration period (1930-2000), which confirmed that the reconstruction of past temperature with the average $\delta^{18}O$ series is suitable (Figure 4A). The RMSE is 0.26, with a RE and a CE of 0.60. However, it appears that the calibration and verification coefficients are significantly changing depending on the period selected for the statistical analysis. This observation implies that the correlation between Tmax and $\delta^{18}O$ series is not stable over the last century even if the correlation stays significant (Naulier *et al*. in press).

Commentaire [NM2]: Information added

These statistical results confirm that the summer temperature reconstructed based on $\delta^{18}O$ values (i-STREC) are representative of the natural variability that existed in north-eastern Canada.

3.2.2. Millennial temperature trends in north-eastern Canada

The i-STREC shows a 0.6°C decrease of maximum summer temperature over the past millennium (Figure 4B), whereas a millennial 0.2°C cooling is roughly estimated for the mean temperature of northern hemisphere (PAGES 2k consortium, 2013). However, our local temperature decrease is in the same order of magnitude as the decrease of summer-months mean temperature reconstructed using pollen in the North American tundra (Viau *et al.,* 2012), and in northern regions of high latitudes (sediment, tree-ring widths, ice core in Kaufman *et al.,* 2009 and tree-ring widths in Esper *et al.,* 2012). This temperature decline over the last millennium is generally attributed to orbital forcing (PAGES 2k consortium, 2013).

The reconstruction suggests that the maximum summer temperature has varied from a maximum of 17.3°C around AD 1008-1010 to a minimum of 14.8°C around AD 1670-1674. The twentieth century was generally cold (mean of 16°C) with an abrupt warming trend during the last three decades (+0.2°C/10 years between AD 1900-1980 and +0.8°C/decade between AD 1980-2010; CRU TS 3.1 data; Figure 4A). Furthermore, two major climatic episodes were also revealed by i-STREC: a warm period during the eleventh and twelfth centuries (mean of 16.5°C) and a cold period from the early fifteenth to the end of the nineteenth centuries (mean of 15.8°C; Figure 4B). These periods are in agreement with the general knowledge of the temperature trends observed globally for the last millennium and correspond to, the Medieval Warm Anomaly (MWA) and the Little Ice Age (LIA), respectively (IPCC 2013, PAGES 2k consortium, 2013). Based on i-STREC data, we associate these two climatic episodes to the ~ AD 1000-1250 and ~ AD 1450-1880 time periods, respectively.

3.2.3. Evidences of contrasted climatic periods

The high summer temperatures of the 11th century (AD ~ 1000-1250; Figure 4B) coincide with peaks previously observed in our study area based on tree-ring width (Gennaretti *et al.,* 2014b; STREC), as well as in Greenland ice cores (Kobashi *et al.,* 2011; Vinther *et al.,* 2009, 2010), tree-ring series from the Canadian Rockies (Luckman and Wilson, 2005) and Fennoscandia (Helama *et al.,* 2002; Figure 5), and large-scale reconstructions (Mann *et al.,* 2009, Ljungqvist *et al.,* 2012, Kaufman *et al.,* 2009, Trouet *et al.,* 2013). Several hypotheses on the forcing of this warm anomaly have been proposed, including a prolonged tendency towards a positive-phase of the North Atlantic Oscillation (NAO; Trouet *et al.,* 2009; Trouet *et al.,* 2012) or a synchronicity between La Niña phase and a warm phase in the Atlantic Multidecadal Oscillation (AMO; Feng *et al.,* 2011; Mann *et al.,* 2009). In northeastern Canada, the NAO has an important impact on winter temperatures but not for summer (Hurrell *et al.,* 2003). In contrast, the AMO influences spring and summer temperatures (Fortin and Lamoureux, 2009) and is partly responsible for the recent sea surface temperature warming of northeastern Canada (Ding *et al.,* 2014). However, the state of the AMO at the beginning of the millennium being unknown, it is difficult to assess its influence on climate during the MWA. Recently, Sicre *et al*. (2014) have demonstrated that during the MWA, the strong Northern Annular Mode (NAM) was concomitant with a strong ice-loaded Labrador Current (LC). This combination could be responsible for a decrease of fresh air from Arctic to eastern Canada and consequently, for an increased temperature along the continent during a part of the medieval period.

Commentaire [NM3]: Information added

Following the MWA, i-STREC emphasize a cold period between ~ AD 1450 and 1880, which can be attributed to the Little Ice Age (LIA; Figure 4B). It is worth noting that a short warming phase occurred between 1510 and 1590 (Figure 4B). Such warm phase also occurred at the eastern Canadian treeline and included the expansion of upright tree growth forms in lichen-spruce woodland (Payette *et al.,* 1989). Overall, the LIA is recorded in several Northern hemisphere temperature reconstructions based on various proxies, even if its length vary among regions (PAGES 2k consortium, 2013). At the hemispheric scale, the LIA is a well-documented cool period (Moberg *et al.,* 2005; Mann *et al.,* 2009; Hegerl *et al.,* 2007), and several causes may have concurred to trigger its occurrence, including a succession of strong volcanic eruptions (Crowley, 2000; Miller *et al.,* 2012, Gennaretti *et al.,* 2014b), millennial orbital cooling (Kaufman *et al.,* 2009; Esper *et al.,* 2012), and low solar radiation (Bard *et al.,* 1997).

In the present study, we compared the i-STREC mean of maximal summer temperatures for MWA (1000-1250), LIA (1350-1850) and the modern period (1950-2000 as defined in IPCC, 2014) and found that the MWA was warmer than the modern period (+0.2°C) and LIA (+0.4°C) in our study area. These results contrast somewhat with Northern hemisphere temperature reconstructions that have determined that the mean annual temperature of the modern period was the warmest in northern Canada (Mann *et al.,* 2009; Ljungqvist *et al.,* 2012). Indeed, the data available for these hemispheric reconstructions in the last IPCC report are scarce for north-eastern Canada (Viau *et al.,* 2012). Clearly, both the i-STREC and STREC (Gennaretti *et al.,* 2014) results indicate that the MWA in northeastern Canada has been the warmest period of the last millennium (Figure 5). The similarities between MWA and the modern period are not a surprise considering that the MWA has been widely studied for its similarities with the modern warming period. Nevertheless, the causes that triggered these periods are likely different (i.e., Landrum *et al.,* 2013; Way and Viau, 2014). Indeed, if the MWA is only controlled by natural processes, it seems that the warming of the modern period results from a combination of natural and anthropogenic causes (i.e, Mann *et al*., 2009; Viau *et al*., in press). By using empirical statistical modeling and global climate models, Way and Viau (2014) have shown that the variance of annual air temperature over the period 1881-2011 in Labrador was explained at 65% if anthropogenic forcing was also included in the model. Even if summer temperature has increased at a lower rate compared to annual air temperature in Labrador, the observed warming (+1.9°C) between 1970 and 2000 is one of the fastest over the last millennium in the region of L20. In the next decades, if warming continues at this rate, temperature will reach a record for the last millennium.

Commentaire [NM4]: Information added

3.2.4. Climatic forcings of the last millennium

Contrary to previous studies, our isotopic series does not emphasize an abrupt LIA onset in response to volcanic forcing such as the AD 1257 Samalas event (Lavigne *et al.,* 2013; Figure 6). Instead, our data suggest that solar radiation was the most influential forcing on Tmax changes in the studied region. Indeed, the most important cooling phases of i-STREC occurred during periods of low solar activity like the Oort (AD 1040-1080), Dalton (AD 1800-1850), Maunder (AD 1600-1650) and Spörer (AD 1410-1480) minima (Figure 6). A simple re-sampling method involving 1000 iterations of re-sampling (bootstrapped) has demonstrated that the low temperature periods were always associated to low solar radiation periods ($p<0.05$). Proposing that solar radiation represents an important control on temperature in north-eastern Canada is in agreement with the hypothesis that the solar forcing was important during the last millennium (AD 1000 to ~1900), except during the modern period (Breitenmoser *et al.,* 2012; Keller *et al.,* 2004), implying that recent anthropogenic impact is the main control at that time. However, even i-STREC is not significantly influenced by volcanism, as determined by superimposed epoch analysis (results not shown), the possibility that successive strong volcanic eruptions combined with solar minima could have contributed to the important LIA cooling in Northeastern Canada cannot be discarded. Strong eruptions and solar minima coincide during the Maunder minimum with the Kuwae eruption, and the Dalton minimum with the unknown (1809), Tambora (1815) and Cosiguïna (1835) eruptions. The role of coinciding natural forcings is also invoked in other paleoclimatic studies that have compared northern hemisphere reconstructions with solar radiation series (e.g., Bard *et al.,* 2006; Breitenmoser *et al.,* 2012; Crowley *et al.,* 2000; Lean *et al.,* 1995; Shindell *et al.,* 2003). These studies have shown that temperature changes were largely due to solar forcing alone during the first part of the last millennial, and to volcanic and solar forcings (i.e, Breitenmoser *et al.,* 2012), or to volcanic eruptions (i.e., Crowley *et al.,* 2000; Keller *et al.,* 2004) during the end of the LIA (after 1600). In addition, Tingley *et al*. (2014) have demonstrated, by analyzing the ring density in trees growing at high latitude, that the trees recorded not only volcanic eruptions but also variations in light intensity. This finding indicates that both isotopes and density of trees can record changes in solar radiations.

The other temperature reconstruction produced for the studied region (STREC) contains a stronger volcanic signal than i-STREC (Gennaretti *et al.,* 2014b). Considering that the two reconstructions are statistically robust, we can assume that they both reflect real trends. In addition, calibrating STREC using the same approach than for i-STREC (i.e. calibration on maximum temperature over the 1930-2000 time period) indicates that methods cannot account for the main differences between the two reconstructions. Consequently, differences in thermal trends between i-STREC and STREC must be caused by their respective sensitivity to climatic triggers and control mechanisms, ring width and $\delta^{18}O$ values. The first important point to bear in mind is that temperature is the main control on changes in ring widths and $\delta^{18}O$ values, but not the only one. Consequently, other climatic parameters (i.e., precipitations, vapor pressure deficit; Naulier *et al.,* 2014) have also generated short and medium variations on the two series, creating an important "climatic noise" at high and medium frequencies, possibly explaining the differences between the reconstructions. However, it is important to recall that the ring width and $\delta^{18}O$ series used to generate STREC and i-STREC display similar long-term climatic trends. This last point is quite important, considering that our main purpose was to identify long climatic tendencies over the last millennium in northeastern Canada.

The second important aspect to consider is that the temperature-linked processes responsible for the variations of ring widths and $\delta^{18}O$ values slightly differ. In the studied region, rings widths are directly influenced by photosynthetic rates, which generally increase with ambient temperatures. In addition, volcanic aerosols blocking light after a major volcanic eruption may also reduce ring growth concomitantly to reduced temperature, explaining the strong influence of major volcanic events on ring width. In contrast, one of the main control on the final tree-ring $\delta^{18}O$ values is the temperature prevailing regionally during cloud mass distillation, as registered in the raindrop signal and transferred to the source water in soils, then through the root system, to the tree. Moreover, the temperature effects on fractionation during distillation and precipitation (Rayleigh process) is not limited to a temperature range, and may record temperature lows that are not necessarily extreme such as those modulated by solar radiations. When strong volcanic events are combined with minimal solar radiations, the strong influence on regional temperature is also detected by $\delta^{18}O$ values of rain drops. These key differences in mechanisms controlling temperature recorded in ring widths and $\delta^{18}O$ values imply that the two proxies may emphasize forcings in a complementary fashion.

As a summary, it appears that ring widths or $\delta^{18}O$ series have strengths and weaknesses as proxy of past climatic conditions. However, the climatic data that can be extracted from the two series can generate complementary information, permitting to highlight several climatic forcings and identify the main regional control on past, present and future temperatures. Nevertheless, there are still needs for further understanding the differences between processes influencing isotopic assimilation and ring-width growth. Such information would be useful for future climatic reconstruction using a multi-indicator approach.

4. Conclusion

1. The cohort sampling method allows reconstructing climatic variability of medium and low frequencies by using fewer samples than other sampling methods, with a high temporal resolution and analytical replication. Our adjustment of the method of joining cohorts, the JP-adjustment method, permits the preservation of $\delta^{18}O$ variability between segments of trees without biasing the millennial $\delta^{18}O$ series.

2. The combination of two statistical models (linear scaling and simple linear regression) has permitted an adequate reproduction of the measured regional temperature, and allowed reconstructing maximum temperature over the last millennium.

3. i-STREC is complementary to the only other reconstruction in the study region (STREC, based on tree-ring width). These two reconstructions should be combined within a multi-parameter approach to increase the proportions of variance explained.

5. i-STREC suggests that the main climatic forcing at play during the last millennium in the studied region was solar activity, but we remain cautious because we base this hypothesis solely on an apparent correlation between reconstructed Tmax and the curve for solar radiations. Clearly, coldest episodes in the L20 area coincide with low solar radiation (Oort, Spörer, Maunder and Dalton), with the exception of an episode in the nineteenth century, during which low solar radiations (Dalton minima) were combined with two successive and strong volcanic eruptions (unknown 1809 and Tambora 1815 eruptions).

6. Overall, i-STREC shows that the Medieval Warm Anomaly (997-1250) was the warmest period of the last millennium in the study region. However, the sudden and rapid temperature increase during the last three decades is one of the fastest over the last millennium (+1.9°C between 1970 and 2000) and if this rapid warming rate persists, the future climate in northeastern Canada may become an issue of concern.

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Figure and table captions

Figure 1. A) Site location (black circle) and meteorological stations (black stars). B) Representation of lake L20, also illustrating the sampling location of subfossil stems (brown marks) and living trees (yellow marks).

Figure 2. Illustration of the sampling strategy. From year 1000 to 2006, cohorts are represented in red for subfossil stem segments (C0-C11), and in green for living trees (CV). The join points are in black on the overlapping periods (JP0 to JP12).

Figure 3. A) Millennial raw $\delta^{18}O$ series (1000-2010) with subfossil segment cohorts (cohorts C0 to C11; illustrated with different colors), living tree cohort (CV; dark pink curve), and join points (blue dash), the adjustment means (black dash) and the number of tree segments used per year (straight black line). The grey envelop represents the analytical error (0.2‰). The legend shows the correspondence between the colours curves and cohorts. B) Millennial $\delta^{18}O$ series adjusted (black line) with standard deviation (grey lines). C) Comparison between $\delta^{18}O$ values of living trees and subfossil stem segments over the common time interval (1860-1956).

Figure 4. A) Comparison between reconstructed (i-STREC, black line) and observed (blue line) JJA maximal temperature and mean square values on the entire period of calibration. B) i-STREC (black line) with 21-year moving average (red line) and observed JJA maximal temperature series from CRU TS3.1 (blue line). In both cases, the dark grey shading represents uncertainty with ±1 RMSE calculated on the 21-year filter values.

Figure 5. Comparison between i-STREC and other temperature reconstructions (data obtained from NOAA). (A) i-STREC from in north-eastern Canada. B) STREC from tree-ring width, in the same region. C) July-September temperature from varved sediments, Baffin Island, Arctic Canada. D) annual surface temperature from GISP 2 ice core, in Greenland. E) May-August maximum temperature from maximum latewood density and tree-ring width, Canadian Rockies. F) July temperature from tree-ring width, northern Finland. Shading based on i-STREC is shown to ease comparison with the other reconstructions compiled: warmer (pink, colder (green) and modern periods (yellow). All reconstructions have been smoothed with a 21-years filter and normalized (1960-1991).

Figure 6. Volcanic and solar forcings. A) I-STREC (reconstructed summer temperature, 21-years smoothed; red line), compared with the well-known solar minima (grey bands) and the solar forcing series (black line; Bard *et al.,* 2003). B) I-STREC reconstructed summer temperature (red line) compared with the volcanic aerosols sulfates (Sigl *et al.,* 2013). The major eruptions are marked: (1) 1257/1258= Samalas, (2) 1456= Kuwae, (3) 1783= Laki, (4) 1809= unknown and 1815= Tambora and (5) 1835= Cosigüina).

Table 1. Summary of the verification statistics for calibrations using the linear scaling and simple linear regression methods for different periods, and using the measured maximal temperature series.

SD is the standard deviation, r^2 is the coefficient of determination (R squared), RMSE the raw mean squared error, RE the reduction of error and CE the coefficient of error.