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Editor  
Hans Linderholm  
*Climate of the past*

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**Subject: Response to reviewers and revised manuscript submission**

Giessen, 23.04.2026

Dear Prof. Linderholm,

We sincerely appreciate Samuli Helama's and the anonymous reviewers' feedbacks which has helped to improve the quality of our manuscript. We have carefully addressed all comments and suggestions and incorporated the recommended revisions throughout the manuscript.

We have responded to the major queries concerning the "Mild Little Ice Age" hypothesis and have shifted the focus of the revised manuscript toward the warming signal after the Little Ice Age. The revised version now highlights temperature variability during the late pre-industrial period, the clear imprint of volcanic forcing, and the magnitude of warming since the early-industrial period. Accordingly, the title of the manuscript is now changed to "*Limited early-industrial warming and strong volcanic imprints in the Caucasus: a first temperature reconstruction based on maximum latewood density*" which better fits the scope and key findings of the study.

We have revised the discussion by comparing the magnitude of 19<sup>th</sup> - and 20<sup>th</sup> -century warming in our reconstruction with nearby records and regional temperature reconstructions, placing our results in a broader spatial context. To avoid overgeneralization, we now use specific calendar dates instead of broader paleoclimatic terms when referring to different periods of the reconstruction in the Section 4.1. This ensures that interpretations remain consistent with the temporal coverage and methodological limitations of the dataset.

We also thank you for pointing out important observation regarding differences between observational and reconstructed data during the late 1970s. Indeed, the reconstruction shows closer agreement with station-based observations than with the gridded product around the 1970s.

This is confirmed by analyzing correlation for the common period with station data, gridded data and reconstructed data available. During the early period (1961–1990), the correlation between station data and the reconstruction is higher ( $r \approx 0.86$ ) than that between reconstruction and the gridded dataset ( $r \approx 0.75$ ). During the recent station data

period (2007–2019), the agreement between gridded data and the reconstruction is stronger ( $r \approx 0.86$ ) but the correlation between the available station data and the reconstruction is lower ( $r \approx 0.73$ ). Thus, overall, there is no general tendency for station data to be superior over gridded data.

A detailed, point-by-point response to all reviewer comments is provided below. We believe that these revisions have strengthened the manuscript and adequately addressed all concerns raised by the reviewers.

On behalf of all the co-authors

Sincerely,

Rupesh Dhyani

## Point-by-point response to reviewer 1:

Dear authors,

I find the study to be technically strong and regionally important. The MXD data are of high quality, the temperature signal is exceptionally robust, and the reconstruction clearly documents volcanic impacts and the magnitude of recent warming. These aspects are not in question.

However, I largely agree with the concerns raised in the accompanying comment regarding the interpretation of Little Ice Age (LIA) conditions. In its current form, the manuscript appears to argue for a “mild LIA” in the Caucasus, while the available data and applied standardisation do not allow this hypothesis to be tested in a rigorous way.

There are three closely linked issues that, in my view, need to be addressed explicitly.

First, **temporal coverage**. The reconstruction begins in the late 17th century, i.e. well within the commonly defined LIA period. As a consequence, the data do not include pre-LIA conditions (13th–14th centuries) against which the magnitude or onset of LIA cooling could be evaluated. The reconstruction can therefore only describe temperature variability during the late LIA and the subsequent transition into the 20th century, but it cannot assess whether the LIA as a whole was mild or severe relative to earlier climate states.

*Response: We thank the reviewer for their assessment of our manuscript. In response, we have revised the manuscript to more explicitly acknowledge the temporal and methodological limitations of the reconstruction and to ensure that all interpretations remain fully supported by the data. To reduce ambiguity, we use specific dates instead of paleoclimatic concepts to describe certain periods of our reconstruction and we adjusted the title now referring to limited warming during the early-industrial period: “Limited early-industrial warming and strong volcanic imprints in the Caucasus: a first temperature reconstruction based on maximum latewood density”.*

Second, **standardisation and low-frequency variability**. The use of series-wise spline detrending, even within a signal-free framework, inherently limits the preservation of multi-decadal to centennial-scale variability. This is a well-known consequence of spline-based standardisation and implies that slow, long-term cooling trends characteristic of the LIA are likely to be attenuated or removed prior to chronology development. As a result, the reconstruction is structurally much more sensitive to rapid, high-amplitude signals (e.g. volcanic cooling, 20th-century warming) than to gradual long-term changes. In this context, the absence of pronounced low-frequency cooling cannot be taken as evidence for a mild LIA.

As noted by the comment by Samuli Helema, a further prerequisite for reliably assessing centennial-scale variability using Regional Curve Standardisation (RCS) is that the regional curve represents a well-balanced distribution of different age classes. I would like to add that this condition alone is not sufficient. A robust regional curve should also be based on material that spans a sufficiently wide range of climatic conditions.

If a chronology is constructed primarily from living trees that established and grew under broadly similar climatic regimes, the resulting regional curve may be biased towards those conditions. In such cases, even an RCS-based approach may have limited ability to distinguish long-term climatic shifts from biological growth trends. This further emphasises that, for datasets lacking both pre-LIA material and strong climatic contrast across the lifespan of the trees, inferences about centennial-scale variability remain inherently constrained, irrespective of the chosen standardisation method.

*Response: To assess the influence of standardization, we compared our signal-free age-dependent spline chronology with two RCS-based chronologies (full dataset and artificially trimmed subset). These experiments show that the RCS versions suffer from end effects and modern-sample bias, indicating that our dataset is not ideally suited for RCS. While RCS can better preserve low-frequency variability, it does not reveal stronger long-term trends in our data. Detailed results of these detrending experiments and our conclusions are provided in our response to Samuli Helama.*

Third, **spatial representativeness**. The conclusions are drawn from a single regional record, whereas the concept of the Little Ice Age is based primarily on large-scale, multi-site reconstructions with broad spatial coverage and millennium-long temporal extent. Comparisons between a temporally and spatially restricted regional chronology and continental-scale European networks must therefore be made with caution, particularly on centennial timescales.

Taken together, these points do not undermine the quality or value of the reconstruction. Rather, they suggest that the interpretation of LIA conditions should be more tightly constrained to what the data can robustly support. In my view, the manuscript would be strengthened by reframing the conclusions to emphasise temperature variability during the late pre-industrial period and the exceptional nature of modern warming, while avoiding broader claims about the severity or mildness of the Little Ice Age as a whole.

I encourage the authors to clarify these limitations explicitly and to adjust the wording of the discussion and conclusions accordingly. Doing so would bring the interpretations into closer alignment with the methodological scope of the study and would substantially strengthen the paper.

*Response: Well-replicated MXD chronologies can provide highly robust and regionally representative temperature signals even when derived from a limited number of sites in temperature-limited environments. Recent work from the European Alps (Esper et al., 2025) shown that MXD-based reconstructions achieve exceptionally strong agreement with instrumental temperatures. This study shows that individual high-elevation MXD chronologies already exhibit strong and coherent temperature signals, and that these signals remain consistent across different valleys and ecological settings. It further illustrates that robust regional temperature reconstructions can be achieved even with relatively limited spatial coverage, provided that the proxy–climate relationship is strong. This perspective is directly relevant to our study, where sampling was conducted above the timberline under conditions where temperature is the dominant growth-limiting factor. The resulting reconstruction explains up to 72% of instrumental summer temperature variance, which is comparable to values reported for Alpine MXD records and indicates that the chronology captures a strong temperature signal. The spatial correlation field presented in Fig. S5 shows that temperature variability of the reconstruction is representative for the wider Caucasus region.*

*In response to the comments from reviewer 1 (and the other comments), the title, Discussion and Conclusion have been reframed to emphasize temperature variability during the early-industrial period, the clear imprint of volcanic forcing, and the exceptional magnitude of recent warming. We believe these revisions bring the interpretation into closer alignment with the methodological scope of the study while retaining the key strength of the reconstruction to resolve robust regional temperature variability.*

Specific examples of formulations that should be revised or constrained (with line numbers):

**Abstract, lines ~24–26**

*“Temperatures in the 18th and 19th century, a period often described as the Little Ice Age, were not significantly colder in the Caucasus than in the first half of the 20th century.”*

Overgeneralises the LIA despite limited temporal coverage. Should be explicitly restricted to the late LIA and to the period covered by the reconstruction.

*Response: Rephrased to “Temperatures in the second half of the 19<sup>th</sup> century were not significantly colder in the Caucasus than in the second half of the 20<sup>th</sup> century”.*

### **Introduction p. 3, l. 73-83.**

The hypothesis is formulated in terms of improved reliability at both high and low frequencies and a “better confined temperature history” at local to regional scales. While this is a reasonable motivation for applying MXD, it would be helpful to clarify that the ability to assess low-frequency variability is temporally constrained by the start of the chronology. As the record begins in 1697, inferences regarding centennial-scale trends are necessarily limited to the late part of the pre-industrial period and cannot be extended to earlier phases of the Little Ice Age. Stating this explicitly here would help align the stated aims with the temporal scope of the data.

*Response: We have revised the text at the end of the introduction to clarify that our reconstruction describes temperature variability during the last 300 years.*

### **Discussion 4.1, lines ~306–307**

*“The minimal differences between mean raw and detrended MXD chronologies give us additional confidence that the developed chronology preserves both high- and low-frequency climate signals.”*

Raw vs detrended similarity is not sufficient evidence for preservation of centennial-scale variability. This should be removed or substantially weakened.

*Response: Rephrased to “Weak age-trends and minimal differences between raw and detrended MXD chronologies imply a limited impact of detrending on the low-frequency climate signals”.*

### **Discussion 4.1, lines P18~387–394**

The statement that the weak LIA signal is “*likely the result of actual regional climate differences and not a methodological deficit*” is not sufficiently supported given the temporal coverage and the applied series-wise spline standardisation. Methodological constraints affecting the retention of low-frequency variability cannot be excluded and should be explicitly acknowledged. I therefore recommend rephrasing this passage to allow for both climatic and methodological explanations, rather than excluding the latter.

Should be explicitly qualified by the start of the record within the LIA and the limitations of spline-based standardisation.

Excludes plausible methodological explanations. Should be rephrased to acknowledge both climatic and methodological factors.

*Response: We have removed any claims regarding a weak LIA in the manuscript and now focus solely on the warming signal. Please see our detailed response to Samuli for further clarification.*

### **References**

Esper, J., Reinig, F., Torbenson, M., del Castillo, E. M., Kunz, M., Arzac, A., Carrer, M., Chen, F., Kadioglu, A. K., Kirdeyanov, A. V., Tejedor, E., Trnka, M., and Büntgen, U.: Pan-alpine summer temperatures since 742 CE, *Dendrochronologia*, 94, 126432, <https://doi.org/10.1016/j.dendro.2025.126432>, 2025.

## Point-by-point response to reviewer 2:

Dhyani et al. present a new summer temperature reconstruction derived from maximum latewood density from 55 *Pinus sylvestris* trees in the Lesser Caucasus, a region where information on past climate conditions are sparse. Thus, the authors indeed fill a critical spatial gap in mid-latitude tree-ring based temperature reconstructions. The paper is very well written and clearly structured.

The focus of the study which is expressed in the statement “Strong volcanic imprints contrast with a mild Little Ice Age” (LIA) is, however, too strong given that the reconstruction does not cover the full LIA (c. 1350 – 1850) and thus is lacking the long-term context and is missing much low-frequency temperature variations. Here, Samuli Helema and one reviewer already provided highly valuable and extensive comments on the issues on detrending and temporal coverage regarding the LIA. Considering those comments and thereby changing the focus of the paper towards highlighting the unprecedented 21<sup>st</sup> century warming would result in a much stronger paper.

Since major points were already addressed, I have only a few minor comments:

*Response: We thank the reviewer for the positive evaluation of our manuscript and for recognizing its contribution in filling an important spatial gap in mid-latitude tree-ring based temperature reconstructions. We also appreciate the helpful suggestions for improving clarity and consistency throughout the manuscript. In line with this and the comments from other reviewers, we have revised the manuscript to reduce the emphasis on the LIA and instead highlight the robust findings of the study. The title, abstract, discussion, and conclusions have been adjusted accordingly.*

I. 125: the abbreviation “TRW” is already introduced in line 55

*Response: The abbreviation “TRW” has been removed.*

I. 137: gridded data itself cannot apply a gap filling and I would suggest to rephrase the sentence to: “...for gridded data a robust sophisticated gap filling was applied...”

*Response: The sentence has been rephrased to “Thus, we complemented the station data with the three nearest gridded temperature data points from the CRU TS 4.09 dataset, which is a pre-processed product derived through interpolation of monthly climate anomalies from extensive weather station observations providing continuous monthly mean temperatures from 1901 to the present (Harris et al., 2020)”.*

I. 141: the second part of the sentence “the correlation between the averaged station-based and CRU-based time series” is redundant and thus can be removed

*Response: The sentence has been removed.*

I. 155 and 165: For the reconstruction a nested approach was chosen where MXD values are dropped and new nest chronologies developed. The development of this “final MXD chronology using bi-weight robust means” is actually not necessary, only when using it for the climate growth analysis. Please clarify. Also, state what data were used for the nested approach, the 55 individual detrended MXD series?

*Response: The description has been revised in the section 2.7 to clarify that the nested approach is based on the 73 detrended individual MXD series from which successive nest chronologies are developed by reducing replication.*

I. 159–161: use “detrended MXD chronology” and delete “or seasonal”

*Response: Revised as suggested.*

I. 173: use “nest chronology” throughout when referring to those as it could be otherwise confusing

*Response: “nest chronology” is now used consistently throughout the manuscript.*

I. 202: Numbers until nine are written in full and hence, change “6 years” to “six years”. Please revise the manuscript accordingly.

*Response: Revised as suggested.*

I. 248: I find that the cold extremes are quite well distributed across the 300 years with three each in the 18<sup>th</sup> and 19<sup>th</sup> century and four cold extremes in the 20<sup>th</sup> century (1700, 1701, 1781, 1810, 1816, 1817, 1914, 1956, 1959, 1967) and thus, I would not say that cold extremes are “clustered mainly in the early 1800s (e.g., 1810, 1816, 1817)”. Please rephrase.

*Response: The sentence has been rephrased to “At the annual scale, the ten coldest years spread over the last three centuries with three each in the 18<sup>th</sup> (1700, 1701, 1781) and 19<sup>th</sup> (1810, 1816, 1817) century and four cold extremes in the 20<sup>th</sup> century (1914, 1956, 1959, 1967), while the nine warmest years (2008, 2010, 2015, 2017, 2018, 2019, 2020, 2021, 2022) are exclusively concentrated in the early 21<sup>st</sup> century”.*

I. 270: when stating correlation coefficients, please use “r =” and for value ranges use a dash (–) (not hyphen). Please revise the manuscript accordingly, i.e. from line 210 onwards.

*Response: Corrected as suggested.*

I. 309: Specify, also throughout the manuscript, that the reconstructions represent the summer season only, thus state “observed June to September temperatures”.

*Response: Revised as suggested.*

Fig. 4: It is difficult to pinpoint the extreme years on the reconstruction using 100-year steps on the x-axis. Please add a finer x-axis labelling. Also the yellow band (outer nest 5–95% band) is not really discernible and thus, please change colour.

*Response: Fig. 4 has been revised as suggested.*

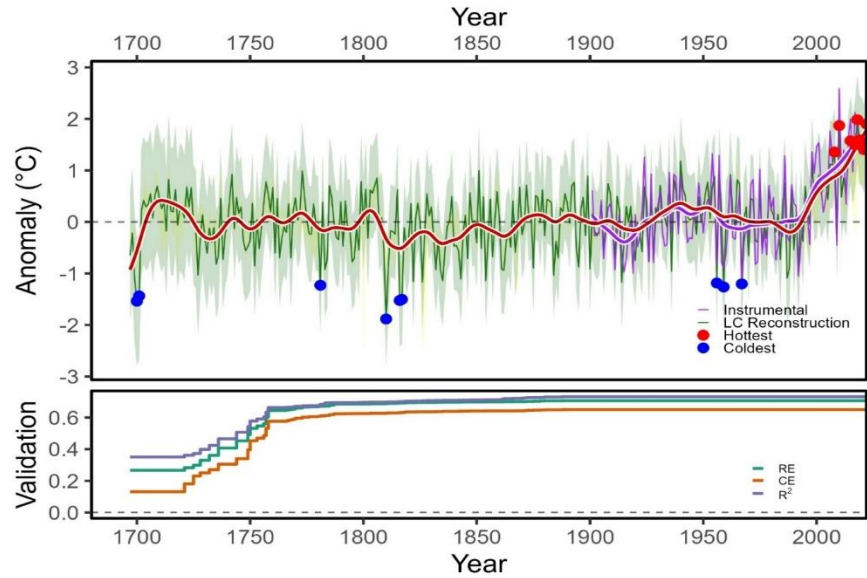


Figure 4: Reconstructed and observed JJAS temperature anomalies (°C) for 1697-2022 relative to 1961–1990. The LC reconstruction is shown as a thin dark-green line with a 20-yr spline (bold red line); instrumental temperature appears as the thin purple line with a 20-yr spline (bold purple line). Calibration uncertainty is conveyed by the inner  $\pm 2\sigma$  model band (light green) and the sampling uncertainty is shown by outer nest 5–95% band (yellow). Red and blue circles mark the 10 hottest and coldest reconstructed years, respectively. The bottom panel shows median RE, CE, and  $R^2$  across nests and the dashed horizontal line indicates zero skill.

Fig. 5: It might be not clear to all readers what NTREND is referring to. Add reference and also the description of the spatial correlation in chapter 2.7.

*Response: We have added a reference in the caption of Fig.5 and the description of the NTREND dataset in section 2.7 to clarify its meaning and context for readers. The description of spatial correlation is already described in section 3.3.*