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 19th century were not significantly colder in the Caucasus than in the first half of the 20th 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 later phase of the Little Ice Age.

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 "The minimal differences between mean raw and detrended MXD chronologies well preserves both high- and 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., Kirdyanov, 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.