

Response to Reviewers

We thank both reviewers for their thorough and constructive comments, which have substantially strengthened the depth and clarity of the manuscript. Below we respond to each comment in turn. Reviewer comments are shown in *italic blue*. In our responses, relevant text from the revised manuscript is shown in *italics*, with the corresponding modifications highlighted in **bold green**.

RC1

Major comments:

First, the novelty of the study should be articulated more clearly in both the Introduction and the Discussion. While the manuscript demonstrates that combining multiple coeval glaciers reduces uncertainties in temperature-precipitation reconstructions, it is not sufficiently explained how this framework advances beyond previous studies that have already used multiple glaciers or multiple climate proxies. I would recommend authors to explicitly identify the conceptual and methodological innovations of their approach, distinguish it from earlier work, and clarify the specific scientific questions that can now be addressed because of the full-Stokes modelling framework

We revised the Introduction to frame our multi-glacier approach as testing whether comparing several coeval, neighboring glaciers can constrain the T–P inversion, given that their contrasting geometry and aspect may induce different T–P sensitivities. We also clarify that our progressive approach — from synthetic single-glacier experiments to real multi-glacier comparisons — is designed to systematically assess how glacier properties and modeling choices affect the T–P solution space, and note that our use of 3D full-Stokes modeling for this type of inversion is, to our knowledge, novel in this context. The Discussion has been revised accordingly for consistency with the Introduction:

Introduction, L59: *A further approach that has proven effective for reducing the temperature–precipitation ambiguity is to combine glacier-extent and lake-balance records from the same period within a coupled glacier–lake system (e.g., Blard et al., 2009; Martin et al., 2018, 2020; Mey et al., 2020). Because glacier and lake mass balance respond differently to climatic conditions, such coupled systems yield a single combination of temperature and precipitation that simultaneously satisfies both the paleolake hydrologic balance and the reconstructed glacier extent. By integrating two independent climate-sensitive systems, this framework effectively constrains climate inversions to a near-unique solution. **Here, we ask whether several coeval and neighboring glaciers — and thus, having experienced the same regional climate — can provide a comparable constraint on the climate inversion, as their contrasting geometry, aspect, hypsometry, and size may induce different T–P sensitivities.***

We test this idea using 3D full-Stokes glacier modeling, which, to our knowledge, has not previously been applied to this type of moraine-based T–P inversion. Full-Stokes modeling provides a comprehensive representation of ice dynamics, thereby minimizing potential biases associated with simplified representations of glacier flow. This allows us to assess whether differences in the inferred climatic conditions arise from the contrasting characteristics of individual glaciers, rather than from limitations of the underlying dynamical model. We follow a progressive approach — from synthetic single-glacier experiments to real multi-glacier comparisons — to assess how glacier properties and model assumptions affect the T–P solution space, and whether the contrasting sensitivities of multiple glaciers can provide complementary constraints on the same climate forcing. We examine glaciers in the vicinity of Zongo Valley in the Bolivian Cordillera Real, where we investigate both synthetic (theoretical) moraines and real moraines that were previously dated to the Early Holocene (~10 ka BP) and the Little Ice Age (LIA, ~1600–1850 CE).

Discussion, Section 5.4, L432: *Nevertheless, and despite using the most comprehensive ice-flow approximation available, we did not obtain better climate constraints than previous studies based on simpler glacier models — **a comparison that, to our knowledge, had not previously been made directly for this type of reconstruction — suggesting that ice-flow complexity is not the limiting factor in this type of T–P reconstruction.** Although it remains unclear how a simpler ice-flow model coupled to the same SMB formulation would perform, we would not expect an improvement in the climate constraint. This limited sensitivity of the results to the ice-flow formulation is likely because topography strongly guides and confines ice flow in mountain glacier settings, so, under steady-state conditions, glacier geometry is primarily controlled by the mass-balance distribution rather than by the specific ice-flow approximation (Oerlemans, 2001; Le Meur et al., 2004). **Differences between ice-flow models become more relevant in transient simulations, where ice thickness and internal deformation actively shape the evolution of glacier geometry, and where a full-Stokes approach would therefore be expected to offer a more accurate representation of the glacier response.***

Second, the uncertainty analysis remains incomplete. The manuscript discusses uncertainties arising from the choice of melt model and glacier-specific responses, but other important sources of uncertainty are only mentioned qualitatively or not evaluated at all. These include moraine age uncertainties, errors in moraine mapping, calibration parameter uncertainty, assumptions regarding equilibrium conditions, precipitation lapse rates, and climate forcing. A more systematic assessment of these uncertainties, either through a sensitivity analysis or an uncertainty propagation framework, would

considerably strengthen the robustness of the reconstructed temperature estimates and provide readers with greater confidence in the conclusions.

We agree with the reviewer that a systematic assessment of uncertainty sources is important to strengthen confidence in the reconstructed temperature estimates and our conclusions. However, our approach already mitigates or encompasses several elements mentioned by the reviewer, as listed below:

- 1) Moraine age and mapping uncertainties are mitigated by our multi-glacier averaging approach, as the influence of any single, imprecisely dated or mapped record is reduced relative to the shared regional signal (Sect. 5.3).
- 2) The assumption of equilibrium conditions is a working hypothesis common to all moraine-based reconstructions, consistent with the steady-state framework adopted here.
- 3) The precipitation lapse rate is not an assumed parameter but is directly constrained by local observations.
- 4) The climate forcing is bias-corrected against local AWS records, so it is also observationally constrained rather than a free assumption.

For these reasons, we did not carry out additional sensitivity tests on these parameters. From our perspective, and following the reviewer's comment, the main source of uncertainty not yet covered in the original submission concerns the calibration parameters of the SMB models. Therefore, we now define minimum and maximum calibration bounds for both melt models, consistent with the observed SMB profiles and glacier outlines (Supplementary Figs. A1, shown below), and propagate these bounds into the T–P anomaly curves as a shaded uncertainty band in Fig. 9 (T–P anomaly curves for the Oerlemans and Hock models on real moraines).

We hope this clarifies the main sources of uncertainty affecting our reconstruction and strengthens confidence in the reported temperature estimates.

Surface mass balance model calibration and validation, Section 3.2.3, L243: *To account for uncertainty in model calibration, we characterized a plausible range of parameter sets around the best-fit calibration. To this end, albedo parameters were kept fixed at their best-fit values, and parameters such as the precipitation lapse rate were kept at their observationally constrained values. We instead varied the melt factors (MF), DDF, and kSW, as these are the parameters controlling the SMB model's sensitivity to temperature and, consequently, the climate reconstruction. For the Oerlemans model, minimum and maximum bounds were defined by varying the snow and ice melt factors (MF_{snow}, MF_{ice}) between 3–5 and 10–20 W m^{−2} °C^{−1},*

respectively, with K_0 adjusted accordingly. For the Hock model, T_{melt} was varied between 0°C and -3°C ; since $T_{\text{melt}} = 0^\circ\text{C}$ did not yield an acceptable fit to the observed SMB profile for either glacier, the upper bound was set at $T_{\text{melt}} = -1^\circ\text{C}$ for both, with DDF and k_{SW} adjusted accordingly (Table 3; Supplementary Figs. A1). For Charquini South, this upper-bound parameter set coincides with the best-fit calibration, as the only combination of DDF and k_{SW} yielding an acceptable fit at $T_{\text{melt}} = -1^\circ\text{C}$ was the best-fit combination itself. These bounds are shown as shaded uncertainty bands in the T - P anomaly curves derived from real moraines (Fig. 9).

Table 3. Calibration parameters and minimum/maximum calibration bounds for Zongo and Charquini South glaciers for the Oerlemans and Hock melt models.

Glacier	Melting model	Bound	α_{snow}	α_{ice}	α_{firn}	$T_{\text{melt}}^{*(a)}$	$M_{F,\text{snow}}^{*(b)}$	$M_{F,\text{ice}}^{*(c)}$	$K_0^{*(d)}$	$DDF^{*(e)}$	$k_{\text{SW}}^{*(f)}$
Zongo	Oerlemans	Max	0.80	0.50	0.70	-	10	20	-25	-	-
		Best-fit	0.80	0.50	0.70	-	10	20	-30	-	-
		Min	0.80	0.50	0.70	-	3	5	-33	-	-
Charquini South	Oerlemans	Max	0.80	0.50	0.70	-	10	20	-29	-	-
		Best-fit	0.80	0.50	0.70	-	10	20	-30	-	-
		Min	0.80	0.50	0.70	-	3	5	-32	-	-
Zongo	Hock	Max	0.70	0.50	0.70	-1	-	-	-	5.0×10^{-3}	9.0×10^{-5}
		Best-fit	0.70	0.50	0.70	-1	-	-	-	3.0×10^{-3}	8.0×10^{-5}
		Min	0.70	0.50	0.70	-3	-	-	-	1.0×10^{-3}	3.0×10^{-5}
Charquini South	Hock	Max	0.70	0.50	0.70	-1	-	-	-	2.0×10^{-3}	8.0×10^{-5}
		Best-fit	0.70	0.50	0.70	-1	-	-	-	2.0×10^{-3}	8.0×10^{-5}
		Min	0.70	0.50	0.70	-3	-	-	-	3.0×10^{-4}	3.0×10^{-5}

*Units: (a): $^\circ\text{C}$; (b,c): $\text{W m}^{-2}^\circ\text{C}^{-1}$; (d): W m^{-2} ; (e): $\text{m w.e. } ^\circ\text{C}^{-1} \text{ day}^{-1}$; (f): $\text{m w.e. } ^\circ\text{C}^{-1} (\text{W m}^{-2})^{-1}$.

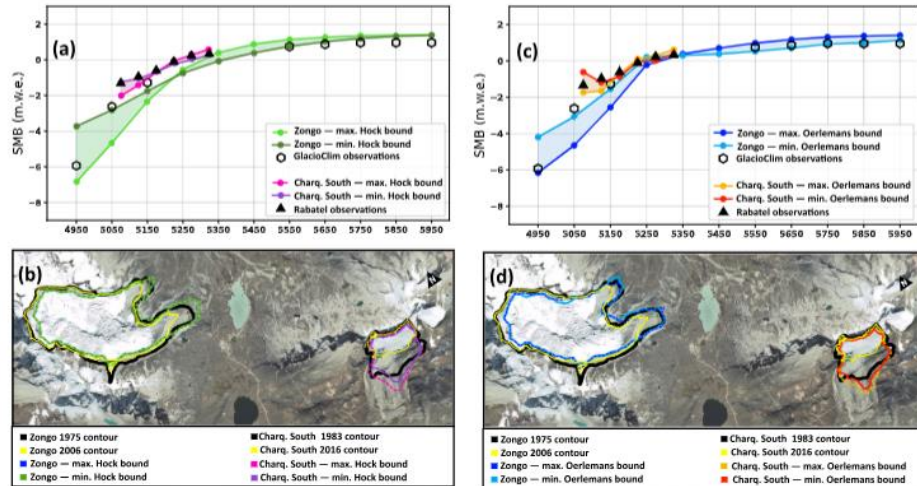
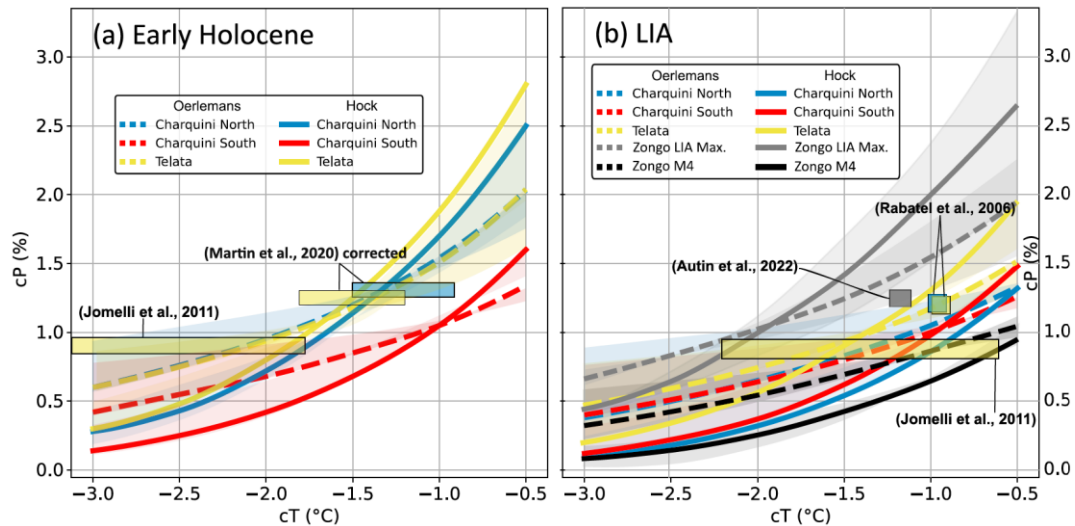


Figure A1. Minimum and maximum calibration bounds for the Hock (a, b) and Oerlemans (c, d) melt formulations, showing modeled vs. observed SMB profiles (a, c) and glacier outlines (b, d).



Updated Fig.9: T - P anomaly curves for Oerlemans (dashed lines) and Hock (solid lines) models on real moraines. Moraines dated from: (a) Early Holocene, (b) LIA. **Shaded bands represent the uncertainty range derived from the minimum and maximum calibration bounds of each melt model.** Pale-colored rectangles depict climate reconstructions from previous studies; colors correspond to the moraine used. Temperature anomalies have been adjusted to our present reference climate for ease of comparison.

Third, the justification for excluding the maximum Little Ice Age Zongo moraine from the final multi-glacier reconstruction requires further support. Although the proposed explanation involving topographic controls and serac collapse is plausible, it remains largely speculative. My advice would be to provide additional geomorphological or modelling evidence supporting this interpretation, or alternatively present quantitative sensitivity tests demonstrating how inclusion or exclusion of this glacier affects the reconstructed regional climate.

The pronounced topographic break at the Zongo glacier front — where the catchment slope changes abruptly, forming a quasi-vertical wall — together with the possibility that the downstream moraines were partly fed by avalanching ice not captured by our model, provides a geomorphological and modelling rationale for treating the mapped maximum LIA extent with caution. We have clarified this interpretation in the Discussion (Sect. 5.3), while acknowledging that the proposed serac-collapse mechanism remains a hypothesis.

In addition, we have added a quantitative sensitivity test comparing the multi-glacier LIA reconstruction obtained with and without Zongo's mapped maximum extent (Supplementary Fig. A2, shown below): including it would shift the reconstructed LIA temperature by -0.42 °C toward a colder estimate. We have added this quantitative result to the Discussion, together with the comparative figure in the Supplement. This helps demonstrate the sensitivity of the multi-glacier averaging approach to individual outlier

records and highlights the importance of a careful climatic and geomorphological interpretation of the moraine record prior to averaging.

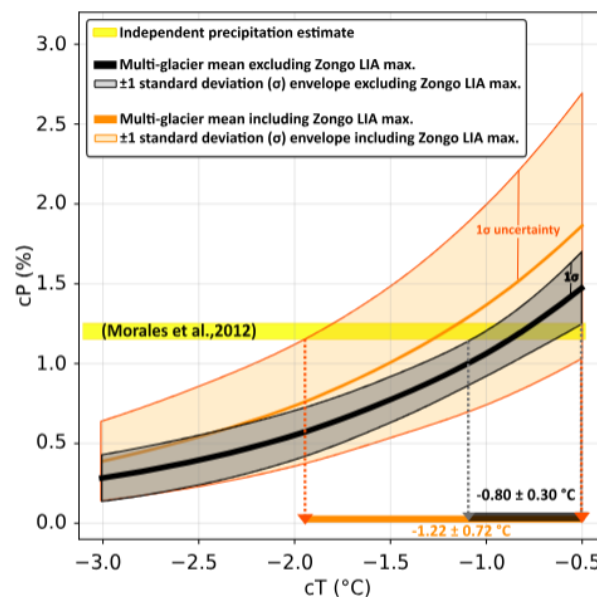


Figure A2. Sensitivity of the multi-glacier average to the inclusion of the Zongo LIA maximum extent in the climate reconstruction.

Fourth, the manuscript would benefit from a clearer discussion of the broader applicability and limitations of the proposed methodology. The study is conducted in a relatively small tropical mountain range where neighbouring glaciers experience similar climatic forcing. It remains unclear how transferable the proposed multi-glacier framework is to other glaciated regions with stronger climatic gradients, different precipitation regimes, larger glacier size variability, or more complex topographic settings. Expanding the Discussion to identify the conditions under which the proposed approach is expected to perform well, and where it may be less reliable, would significantly increase the impact of the paper and its relevance to a broader paleoclimate audience.

We added a new Discussion subsection (Sect. 5.5, “Broader applicability and limitations”) to discuss the transferability of our approach and the factors that may affect its reliability. This new subsection is included below. We clarify that, although the framework is theoretically transferable to other glaciated regions, its application requires coeval, neighboring glaciers with well-preserved moraine records, and that the appropriate spatial and temporal configuration may depend on the study area and the climatic signal being reconstructed. We further discuss how the climatic and glaciological setting may influence the T–P constraint, noting that the glaciers considered here share a broadly similar precipitation regime and strong topographic confinement, and that applications in settings with stronger contrasts between glaciers would help assess the broader applicability of the approach. We also discuss the equilibrium assumption underlying moraine-based

reconstructions and the possibility of stochastic glacier excursions. In this context, the multi-glacier approach limits the effect of glacier-specific stochastic excursions on the reconstructed climate, while the agreement between the resulting T–P curves can help identify potential deviations from the common climatic signal, although this does not fully resolve this source of uncertainty.

5.5 Broader applicability and limitations

From a theoretical point of view, the multi-glacier full-Stokes framework presented here is transferable to other glaciated regions, subject to a few practical and conceptual considerations. First, its application requires a set of coeval, neighboring glaciers with well-preserved moraine records. The appropriate spatial and temporal configuration likely depends on the characteristics of the study area and the climatic signal being reconstructed. Therefore, testing different glacier separations and degrees of temporal overlap would help assess how these factors affect the reliability of the approach. Nevertheless, the approach may remain useful even when the available glaciers are fewer or more widely spaced, particularly in regions where other paleoclimate constraints are limited. Second, the approach relies on the availability of present-day observational data for at least one glacier in the study area, without which melt model parameters cannot be independently constrained.

Besides, the T–P constraint provided by our approach likely depends on the climatic and glaciological setting of the study area. The glaciers studied here differ in hypsometry and aspect, yet present a similarly snow-dominated precipitation regime and are similarly confined by steep valley topography. The extent to which these other features influence T–P sensitivity, and whether stronger contrasts between glaciers could provide more complementary constraints on the reconstruction, remains unclear. It would therefore be valuable to test our approach in settings where glaciers differ more strongly from each other in these respects.

A further limitation inherent to our approach, and to most glacier-based paleoclimate reconstructions, is the assumption that a mapped moraine reflects a glacier in equilibrium with a sustained climate state. However, glacier length can fluctuate substantially in response to interannual climate variability alone, even under an otherwise stationary long-term climate (Oerlemans, 2000; Roe and O’Neal, 2009; Roe, 2011; Doughty et al., 2017). Such fluctuations could, in principle, produce a moraine at a given position without reflecting a genuine, sustained shift in temperature or precipitation. In this context, the multi-glacier approach limits the effect of glacier-specific stochastic excursions on the reconstructed climate, while the agreement between the resulting T–P curves can help identify potential deviations from the common climatic signal: closely grouped curves support a

common climatic interpretation, whereas a strongly deviating curve may point to glacier-specific processes or a stochastic excursion. However, this approach does not fully resolve this source of uncertainty, which remains an open challenge for the field.

Minor comments:

P2 L18-19 - Glaciers continuously grow and shrink in response to climate variations, reshaping the landscape beneath them and leaving behind characteristic features of glacial erosion and deposition.

Citation is missing here. Please add: <https://doi.org/10.4324/9780203785010>
Citation added.

P2 L22-23 - Such moraines provide valuable information about former glacier boundaries, and their distribution in the present-day landscape is often assumed to reflect ice positions during climatically stable periods.

Citation is missing here. Please add: <https://doi.org/10.1016/j.geomorph.2014.07.030>
Citation added.

P2 L35-36 - A key challenge in using ice-marginal moraines as paleoclimate proxies is that a single glacier extent can result from different combinations of precipitation and temperature.

Citations are missing here. Please add:

- <https://doi.org/10.3390/rs17091486>
- <https://doi.org/10.1080/04353676.2025.2521180>

We have added both citations to the first paragraph of the introduction, where we felt they were a better fit.

The scale bar is missing from Figure 3.

We believe the reviewer may be referring to Figure 4, as Figure 3 is a schematic illustration of the methodology and does not represent real-world spatial data requiring a scale bar. A scale bar was added to Figure 4, the 3D finite element mesh of Zongo Glacier.

The scale bar and the coordinates from Figure 5.

Both the scale bar and coordinates were added to Figure 5.