

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**.

RC2

Major issues:

The background and articulation of the scientific problem are underdeveloped. Citations are concentrated within a relatively small research group, and several important studies are missing. Here are some suggested citations which include a range of approaches previously taken with models of different complexity, as well as a review of reconstructing past climates from glaciers.

We have broadened the literature background by considering the suggested citations:

- Reconstructing spatially variable mass balances from past ice extents by inverse modelling <https://www.cambridge.org/core/journals/journal-of-glaciology/article/reconstructing-spatially-variable-mass-balances-from-past-ice-extents-by-inverse-modeling/D05D2D15D5DE670D0D86ECCA653E1891>
Citation added in the second paragraph of the introduction as an inverse-modelling approach.
- A 2-D numerical model of snow/ice energy balance and ice flow for paleoclimatic interpretation of glacial geomorphic features. <https://www.sciencedirect.com/science/article/abs/pii/S0277379103000817>
Citation added in the second paragraph of the introduction as an SEB model.
- Constraints on Southern Hemisphere tropical climate change during the Little Ice Age and Younger Dryas based on glacier modeling of the Quelccaya Ice Cap, Peru. <https://www.sciencedirect.com/science/article/pii/S0277379115300676>
Citation added in the second paragraph of the introduction as an SEB model.
- Reconstruction of Past Glacier Changes with an Ice-Flow Glacier Model: Proof of Concept and Validation <https://www.frontiersin.org/journals/earth-science/articles/10.3389/feart.2021.595755/full>
Citation added in the second paragraph of the introduction as a PDD-based approach.
- Reconstructing Climate from Glaciers. <https://doi.org/10.1146/annurev-earth-063016-020643>

Citation added in the third paragraph of the introduction as a key review framing the T–P equifinality problem.

We also revised the Introduction and Discussion to more explicitly articulate the scientific problem addressed by our approach and its novelty relative to previous studies:

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.**

A specific omission is citation of the influence of interannual climate variability on glacier mass balance and the potential for glaciers to undergo a "random walk" in response to stochastic climate forcing, as developed by Hans Oerlemans and then extended by Gerard Roe. These findings have implications for the steady state reconstruction of glaciers from moraine positions and this should be briefly discussed. For example:

- The response of glaciers to intrinsic climate variability: observations and models of late-Holocene variations in the Pacific Northwest
<https://doi.org/10.3189/002214309790152438>
- An exercise in glacier length modeling: Interannual climatic variability alone cannot explain Holocene glacier fluctuations in New Zealand.
<https://www.sciencedirect.com/science/article/abs/pii/S0012821X17302170?via%3Dihub>
- Holocene glacier fluctuations: is the current rate of retreat exceptional?
<https://www.cambridge.org/core/journals/annals-of-glaciology/article/holocene-glacier-fluctuations-is-the-current-rate-of-retreat-exceptional/B8B127380CB133A11533CDE1A451F67E>

We incorporated all three suggested references (Oerlemans, 2000; Roe and O'Neal, 2009; Doughty et al., 2017) in a new paragraph added to **Sect. 5.5**, copied below, which discusses how interannual climate variability can challenge the steady-state assumption underlying moraine-based reconstructions, and how our multi-glacier approach partially mitigates this issue.

Sec.5.5, L457: 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.

Because models have different sensitivity to temperature and precipitation, precipitation variability can be used to provide a uncertainty window of past temperature reconstructions. And the bounds can be reasonably tight. More could be said about this in the introduction. Also the effect of precipitation field on inversion results has been considered by Ann Rowan and should be cited: Late Quaternary glacier sensitivity to temperature and precipitation distribution in the Southern Alps of New Zealand <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2013JF003009>

We expanded the Introduction (Sec. 1, L39) to add more nuance on the T–P ambiguity, including the suggested reference (Rowan et al., 2014) on the influence of precipitation-field uncertainty on inversion results. The updated passage, reproduced below, also clarifies why this uncertainty translates into comparatively modest uncertainty in reconstructed temperature.

Introduction, Sec.1, L39: *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 (see Mackintosh et al., 2017, for a review). Consequently, paleoclimate inferences based on glacier reconstructions must remain limited to qualitative comparisons of the timing and relative magnitude of glacial advance. This ambiguity is partly mitigated by the fact that glacier mass balance is typically more sensitive to temperature than to precipitation, since temperature affects both surface melt and the phase of precipitation. As a result, comparatively large changes in precipitation are needed to offset a given temperature anomaly — glaciers typically require a ~40% increase in precipitation to compensate for ~1°C of warming (Oerlemans, 2001). This asymmetry means that even substantial uncertainty in the spatial distribution of precipitation may translate into comparatively modest uncertainty in reconstructed temperature (Rowan et al., 2014); however, obtaining an independent precipitation estimate remains a major challenge.*

Minor issues:

Line 33. 'In contrast, SEB models aim for greater accuracy'.

SEB models have more complete representation of physical processes but are not necessarily more accurate. Rewrite this.

Revised, L33: In contrast, SEB models offer a more complete representation of the physical processes governing melt [...].

Line 34. 'the limited availability of past meteorological data leads to an underdetermined problem in paleoclimate studies.'

Not sure what this means. Underutilised? Please clarify. Another issue is lack of data to constrain model parameters (not just meteorological forcings).

Revised, L36: Although SEB models are applicable to modern, well-instrumented periods (e.g., Autin et al., 2022), applying them to past climates is limited by the scarcity of both meteorological forcing data and observations needed to constrain model parameters.

Line 35. 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. While this is true, it is worth adding some nuance. Temperature and precipitation have different sensitivities and this could be cited. E.g. how much temperature change is needed to offset a % change in precipitation. Also, one should remind the reader that temperature affects melt AND precipitation phase.

This point was already addressed in response to the major comment regarding the T–P sensitivity asymmetry (citing Oerlemans, 2001, and Rowan et al., 2014), where we added the ~40%/1°C offset and the role of temperature in controlling both melt and precipitation phase.

Also, other meteorological variables can also have an effect even though their influence is smaller. E.g. cloud cover influencing incoming solar radiation, and wind speed and humidity affecting turbulent exchange. This should be mentioned prior to moving on to temp and precip.

Revised, L34: [...] physical processes governing melt by accounting for spatial and temporal variations in numerous meteorological parameters — such as albedo, insolation, cloudiness, wind speed, and humidity — that influence radiative and turbulent energy exchange at the glacier surface.

Figure 2. Typical climatic conditions in the upper reaches of the Zongo-Charquini area. The red curve shows the mean monthly temperature, and the light blue bars show the mean monthly precipitation at 5050 m a.s.l.

- Is this at about the terminus elevation? State how this elevation relates to nearby glaciers.

We updated the Figure 2 caption to clarify this: "*Typical climatic conditions in the upper reaches of the Zongo-Charquini area. The red curve shows the mean monthly temperature, and the light blue bars show the mean monthly precipitation at 5050 m a.s.l.*"

Data are averaged over 9 non-continuous years between 1999 and 2016 and **come from the SAMA automatic weather station (AWS; 5,050 m a.s.l.)** on Zongo Glacier (16°S, Cordillera Real), **located near the present-day terminus of Zongo Glacier**. Raw data are available at: <https://glacioclim.osug.fr/Donnees-des-Andes>."

We also added the location of the SAMA AWS to Figure 1, showing its position near the present-day terminus of Zongo Glacier and allowing a direct visual comparison between the AWS elevation and the glacier fronts.

L 79. 'flowing meltwaters', meltwater – should be singular
Corrected.

Table 1. Characteristics of the four study glaciers
Add terminus elevation
Elevations added.

Table 2. How were assumptions made about past precipitation levels?

A footnote was added to Table 2 specifying how past precipitation (cP) was estimated for each case: Autin et al. (2023), from on-glacier AWS record; Jomelli et al. (2011), from PMIP-II GCM ensemble; Rabatel et al. (2008), from ELA-based inversion; Martin et al. (2020), from lake–glacier inversion.

'This approach is currently among the most accurate for simulating ice flow'
Comprehensive does not necessarily mean accurate

Revised, L125: This approach is currently among the most comprehensive for simulating ice flow in mountain glacier environments, as it solves the full stress field governing ice flow without the simplifying assumptions of lower-order approximations.

L 154. Oerlemans (2001)and Hock (1999) models,
Needs gap
Corrected.

L 400. 'The limited sensitivity of the results to the ice-flow formulation is likely because, in mountain glacier settings, topography strongly guides and confines ice flow, so in a steady state simulation, glacier geometry is primarily controlled by mass-balance distribution rather than by the specific ice-flow approximation.'

This is a long-held understanding dating back to at least Oerlemans but there is no citation.

Two citations added: Oerlemans (2001) and Le Meur et al. (2004).

L 423. In this context, multi-glacier approaches provide a robust framework for estimating regional climate. I agree and you could cite work that has previously done this.

E.g. Last Glacial Maximum climate in New Zealand inferred from a modelled Southern Alps icefield <https://www.sciencedirect.com/science/article/abs/pii/S0277379112001850>

Citations added: Golledge et al. (2012).