

Late Quaternary glacial maxima in Southern Patagonia: insights from the Lago Argentino glacier lobe

Romero et al. (2024)

We thank both reviewers for their positive and thoughtful commentary on the manuscript. The proposed changes undoubtedly improve this work. The two reviewers shared similar feedback about the interpretation of the older landforms (Arroyo Verde moraines), so we provide a single response for addressing this concern. Minor comments are addressed individually. The attached document contains the reply to the reviewer.

Reviewer comments are presented in their original format and our response is in blue text, with manuscript changes in blue and **bold**. To streamline review, for small changes on grammar, word choice, etc. we write 'Done', 'Addressed', and/or 'Noted' to signify we have made the change.

Authors reply to Dr. Christopher Darvill – RC2

This manuscript presents an important new reconstruction of the Lago Argentino glacier in Argentine Patagonia based on geomorphological mapping and Be-10 and IRSL dating of glacial landforms. The authors' principle finding is that the glacier reached its maximum extent during Marine Isotope Stages 6 and 3, with no evidence found for an MIS 2 / global Last Glacial Maximum limit (although they note it may still exist). The new evidence adds to a growing body of work from the Southern Andes showing numerous glaciers were more extensive prior to the global Last Glacial Maximum during the last glacial cycle. They add weight to ideas in the literature that this could have been caused by longer, colder winters earlier during the last glacial cycle, combined with movement of the Southern Westerly Wind system. Overall, the paper provides a valuable new record for pre-LGM glacial activity in Patagonia and will be a useful addition to the literature. The paper is well-written and presented, with excellent figures and clear discussion. This is an impressive piece of work. I have only one major issue relating to the authors' interpretation of older ages in the Lago Argentino system—which I believe needs amending throughout the manuscript—and offer an additional list of minor changes that I hope might also strengthen their final paper.

Dr. Darvill's points about the older moraine system are well-taken, and we modify the interpretation and discussion throughout the manuscript, which we detail below.

Major revision

The MIS 3 glacial limit is convincing; the older glacial limit assigned to MIS 6 much less so and should be handled more speculatively. The manuscript currently presents this limit as unambiguously dating to MIS 6 within the abstract, discussion and conclusion, but there are two major issues with this interpretation based on the data presented:

The older Arroyo Verde II limit is assigned to MIS 6 based on only four exposure ages: two in good agreement at ~163 ka, one younger at ~132 (roughly on the MIS 5/6 boundary), and one older at ~243 ka (roughly on the MIS 7/8 boundary). What these clearly show is that the Lago Argentino glacier was more extensive than its MIS 3 El Tranquilo I limit at some point during the Mid-to-Late Quaternary: a valuable conclusion and important addition to the literature. However, the conclusion that this is an unequivocal MIS 6 glacial limit seems too strong, particularly without other supporting evidence (e.g. additional dating approaches and limiting glacial limits, as per Leger et al., 2023, *Climate of the Past*). I find the rationale for

excluding the older exposure age unclear and not reflective of other approaches in the literature, and either way do not see a strong enough body of evidence for such a strong MIS 6 conclusion. In addition:

Older (e.g. > MIS 2) glacial limits across the Southern Andes have proven challenging to date, with a large body of work demonstrating potential issues, particularly involving dating boulders on moraines like this study. There are lots of examples from the literature, but a good starting point is Hein et al. (2017; Quaternary Science Reviews). Hein et al. show that boulders on older limits may typically underestimate glacial activity quite substantially (e.g. by a glacial cycle). This makes rejection of the older exposure age and categorical assignment of the Arroyo Verde II limit to MIS 6 problematic. Even without the older age, so few ages should be treated more cautiously, particularly given work around Lago Buenos Aires has shown substantial numbers of moraine boulders may still underestimate the timing of glacial retreat.

In summary, it is quite possible the Arroyo Verde II limit does indeed date to MIS 6, but I do not find sufficiently convincing evidence presented here for that conclusion to be so strong. Better to consider MIS 6 as a possibility, but also to consider that the limit may be older. The older exposure age should not be rejected so readily, and the abstract, discussion and conclusion updated to consider a variety of possibilities. I also urge the authors to update their Figure 6, both to factor in the potential for an older limit (i.e. include the older age), and to consider a greater number of existing records in Panel (B) to reflect the fact that numerous MIS 8 limits also exist in Patagonia.

We appreciate both reviewers' thorough commentary on this section of the manuscript. We concur with their main concern about our interpretation of the older glacial landforms mapped and dated in this work. Accordingly, we provide a modified version of our interpretations to account for the fact that the nature of our dataset cannot precisely resolve the timing of occurrence of these landforms to an individual Marine Isotope Stage. Therefore, we acknowledge that given our small number of samples and the existing literature on glacial landforms older than 100 ka (Hein et al., 2009; 2011; 2017; Darvill et al., 2015; Mendelova et al., 2020; Leger et al., 2023), the Arroyo Verde moraines could correspond to MIS 6 or MIS 8. This extends our interpretation to include an older advance and highlights an avenue for future research. This change is reflected throughout the paper, including in the abstract, conclusion, and Figure 6.

Minor suggestions

Line 71: "a relative ages"; there's a plural mismatch.

Done.

Line 73: Can you specify which you mean by "these moraines", you listed four systems, but I think you are just referring to the Puerto Banderas at the end of the preceding sentence.

We moved that sentence to the end of the last paragraph to improve readability as follows: **Lastly, Strelin and Malagnino (1996, 2009) suggested that the Lago Argentino glacier lobe readvanced and deposited the Puerto Banderas moraines westwards of El Tranquilo moraines. The latter are known to date from the Antarctic Cold Reversal, deposited about 10 km from the modern ice from at ~13,000 cal yrs before present (Strelin et al., 2011).**

Line 75: I think you mean Caldenius' framework, not Strelin (the last work you cited). I suggest moving the final sentence in Line 74 to the end of the next paragraph (e.g. Line 81) so the chronology of work is in order.

Done. We modified parts of this section to improve the narrative flow so that the chronology of the work is in order as stated in the comment above.

Line 86: "Last two glaciations" is ambiguous (in terms of them/you naming them? Or in terms of timing?) You can just state that you only focus on the Arroyo Verde and El Tranquilo moraines, or provide their stratigraphic order.

We agree with the reviewer, and we modify the text to simplify the flow of the paragraph: **For this work, we only focus on the Arroyo Verde and El Tranquilo moraines, as identified by Strelin and Malagnino (1996) (Fig.1C).**

Line 133: I'm not sure this scans quite right: I think you are deciding to report with zero erosion given ages overlap within uncertainties and doing so does not alter your main findings. Perhaps adjust the wording here because I do not think you can assume the erosion rate was zero based on the evidence provided.

Wording was modified to make it clear that despite erosion rates being non-zero, we still report our ages with an erosion rate equivalent to zero, given that using different erosion rates does not alter the main implications of this work. Modified as follows: **Since the outcomes of using different erosion rates (Table S1, Fig. S6) do not change the main results of this work and given that age differences overlap within analytical uncertainties, we use an erosion rate equivalent to zero for all the samples for our reported ages and interpretations.**

Line 144: Blomdin et al. used IRSL in southern Patagonia; perhaps a useful reference here (Blomdin, R., Murray, A., Thomsen, K.J., Buylaert, J.P., Sohbati, R., Jansson, K.N. and Alexanderson, H., 2012. Timing of the deglaciation in southern Patagonia: Testing the applicability of K-Feldspar IRSL. Quaternary Geochronology, 10, pp.264-272.)

We thank the reviewer for pointing out this study. We added this reference to the text and modified it accordingly: **Although OSL dating of quartz has been performed in Patagonia (Smedley et al., 2016), lithologies local to the Río Santa Cruz contain little quartz. Therefore, we apply IRSL dating of feldspar grains, as previously performed in other glacial settings within southern Patagonia (Blomdin et al., 2012).**

Line 166: Should "by moraine ridges" be "of moraine ridges"?

Noted and modified.

Line 182: Figure 3: Please include photos of all sampled boulders, if possible. It is useful for assessing what was sampled, and for anyone wanting to revisit sample sites in the future.

Figure 3 includes photos of boulders sampled for El Tranquilo I and Arroyo Verde moraines. On the other hand, Figure 4 includes field photos of sampled boulders from El Tranquilo II moraines.

Line 191: Point to Figure S2 again.

Done.

Line 188: Should be "inboard of", I think.

Noted and modified.

Line 194: "by in"; should be one or the other.

Noted and modified as follows: **by Strelin and Malagnino (1996).**

Line 203: "glacial transgressive facies" implies overlapping / overriding glacial sedimentology to me, but do you mean glaciofluvial, like the rest of the section? Perhaps you are referring to moraines overriding glaciofluvial features? In which case, start with the glaciofluvial features about which this section focusses and then explain that some landforms are indicative of glacial transgression.

We removed the lines: 'glacial transgressive facies', since they belong to the glaciofluvial section, and it confuses the narrative flow here.

Line 211: Why are meltwater channels not described in Section 4.1.3 on Glaciofluvial features?

Done and moved to glaciofluvial.

Line 213: Why are palaeo(lacustrine) features mentioned here again, rather than just in Section 4.1.4 on Glaciolacustrine features?

Done and moved to glaciolacustrine.

Line 249: The rationale for excluding the oldest age here and not the youngest is unclear. With only four ages, I question whether any samples should be removed at all. See broader point about these older ages in the major revisions section. There is a good argument that removing outliers should be done with great caution, or that all ages should be kept in and metrics such as the median be used instead (outlined in Dortch, J.M., Tomkins, M.D., Saha, S., Murari, M.K., Schoenbohm, L.M. and Curl, D., 2022. A tool for the ages: the probabilistic cosmogenic age analysis tool (P-CAAT). *Quaternary geochronology*, 71, p.101323.) Additionally, there is a lot of work on understanding age distributions from these sorts of environments in Patagonia that would counter you rejecting older ages as inherited (Kaplan, M.R., Douglass, D.C., Singer, B.S., Ackert, R.P. and Caffee, M.W., 2005. Cosmogenic nuclide chronology of pre-last glacial maximum moraines at Lago Buenos Aires, 46 S, Argentina. *Quaternary Research*, 63(3), pp.301-315.; Hein, A.S., Coge, A., Darvill, C.M., Mendelova, M., Kaplan, M.R., Herman, F., Dunai, T.J., Norton, K., Xu, S., Christl, M. and Rodés, Á., 2017. Regional mid-Pleistocene glaciation in central Patagonia. *Quaternary Science Reviews*, 164, pp.77-94.)

We agree with the reviewer and consider all the ages for the oldest landform for our calculations, without excluding any result. We report the mean age and the standard deviation of this calculation, and we modify the interpretations accordingly. Additionally, we report the weighted mean and weighted standard deviation in Table 2.

Line 250: Correspondance with MIS 6 needs to be much more speculative here.

We agree, and we modify this section following advice from both reviewers. For more information, please refer to the modified interpretation of the Arroyo Verde moraines.

Line 258: The wording does not quite work here; needs slight editing.

Done and modified as follows: **Although our ¹⁰Be ages indicate that the El Tranquilo I and II moraines are statistically indistinguishable, our mapping indicates that they are stratigraphically distinct, and our dataset indicates that these moraines were occupied and abandoned during MIS 3 (57 – 29 ka; Lisiecki and Raymo, 2005), and that this advance constitutes the largest extent of the Argentino glacier lobe during the last glacial cycle.**

Line 250: Here and elsewhere (so perhaps state if it applies to all), explain what constitutes the uncertainty here, and if it is weighted or not.

In the text, we report the ages for each moraine complex as the mean and the associated standard deviation. Additionally, we report the weighted mean and weighted standard deviation in Table 2. For this review, we clarify this in the text, for example, in Table 2 caption, as follows: **We report mean moraine age and standard deviation (bold), the weighted mean and standard deviation, and outliers (*).**

Line 260: I think the word "preserved" needs inserting, as it's possible (though unlikely) that moraines recording a more extensive advance were subsequently destroyed by outwash from the El Tranquilo advance in such a topographically-constrained system.

We agree with the reviewer, and we added the word preserved to Line 260 to note that a more extensive advance could have been overprinted by the MIS 3 advance and the one we dated is the largest preserved advance of the Lago Argentino lobe during the last glacial cycle. We modified the text accordingly: **...and this advance constitutes the largest preserved extent of the Argentino glacier lobe during the last glacial cycle.** Additionally, we add more text in line 309 (section 5.4.1 Comparison with other glacial records during Marine Isotope Stage 3 [MIS 3]) the following: **We determine that this outlet lobe reached its maximum extent during MIS 3, when it deposited the El Tranquilo I and II moraines ~120 km away from the modern ice front, constituting the earliest and largest preserved advance of the last glacial cycle.**

Line 262: Here, please give the raw mean age and associated error before moving on to explain why you are removing some ages and providing an updated mean and error.

Done. We added the mean age and the standard deviation of all ages before outlier removal.

Line 265: "the valley center".

Done.

Line 265: Small boulders do not inherently indicate exhumation, but they might be more susceptible to it if it occurred. Alter framing to reflect this here.

Done. We modified the text as follows: **For instance, boulders around valley-center rarely exceed half a meter in height, making these smaller boulders more susceptible to exhumation that could result in younger ages.**

Line 268: Be clear throughout about number of samples. E.g. here "we exclude three ages".

Addressed.

Line 280: Figure 6: This should include all ages, so extend back to >243 ka. The moraine ages are rather selective here. A classic of the region—Lago Buenos Aires—is missing (e.g. Kaplan's work, and Hein et al., 2017), as is Hein's work in Lago Pueyrredon. Their chronologies are highly relevant for this work.

We modified figure 6 to include additional relevant studies to support our interpretations, such as Lago Buenos Aires and Lago Pueyrredón.

Line 281: I feel this section needs to better reflect uncertainties in the new chronology; see major revisions.

Agreed. We modified this section and expanded our discussion to include the paleoclimate implications of our record from MIS 6 through MIS 8.

Line 300: Not clear why this is a separate section; it could be added to the start of Section 5.4.1

Addressed and modified.

Line 323: "a millennial-scale moraine chronology"?

Done.

Line 359: Here and elsewhere, worth reflecting that Davies et al. looked at 35 ka to present, so were not necessarily saying maxima occurred then, just that advances were not exceeded after that point.

We acknowledge that the PATICE reconstruction does not imply that the Patagonian Ice Sheet reached maximum extent at 35 ka, therefore we cite other studies involving glacial advances that occurred during MIS 3. We modified the sentence in Line 359 accordingly, and we refer the reader to section 5.4.1 'Comparison with other glacial records during Marine Isotope Stage 3 (MIS 3)', to make our point clearer.

Line 361: Mendelova et al. (2020) talked about the role of ice masses changing moisture patterns and should be referenced here (Mendelová, M., Hein, A.S., Rodés, Á. and Xu, S., 2020. Extensive mountain glaciation in central Patagonia during Marine Isotope Stage 5. *Quaternary Science Reviews*, 227, p.105996.).

Done and added to line 365.

Line 416: This does not sound right. There is evidence for glacial activity (retreating from moraines) during the Holocene (e.g. Sagredo et al., 2021; Reynhout et al., 2019; Strelin et al., 2014; Kaplan et al., 2016; Garcia et al., 2020). See Briner & Darvill 2024 for reference (<https://doi.org/10.1016/B978-0-323-99931-1.00198-7>). You cite some of these papers, so I wonder if it is just unclear what you mean here.

We agree with the reviewer that the last sentence of the penultimate paragraph as well as the last sentence of the last paragraph would benefit from reorganization. We note that during the Holocene, several glacial advances are recognized in Patagonia (Sagredo et al., 2021; Reynhout et al., 2019, 2022; Strelin et al., 2014; Kaplan et al., 2016; Garcia et al., 2020, Hall et al., 2020). We emphasize that our aeolian record coincides with periods of drier and warmer conditions that agree with the paleolimnological and paleoecological record from Lago Cipreses (Moreno et al., 2014; 2018). Additionally, this record coincides with a paucity of glacial advances during these drier/warmer periods. We modified the text accordingly: **While evidence for glacial growth is available from Southern Patagonia during the Holocene (Strelin et al., 2014; Kaplan et al., 2016; Reynhout et al., 2019; Sagredo et al., 2021; García et al., 2020), the lack of evidence for glacial advances at ~10.8 ka and ~3.6 ka coincides with these warm and dry periods defined by pollen assemblages (Moreno et al., 2018).**