

Review of Cuzzone et al. 'Modeling the timing of Patagonian Ice Sheet retreat in the Chilean Lake District from 22-10 ka', *The Cryosphere*

Paper Summary:

Cuzzone et al. present a numerical ice sheet model reconstruction of the Patagonian Ice Sheet in the region of the Chilean Lake District (CLD), focusing on the LGM and subsequent deglaciation. The CLD is an area that is generally lacking empirical data and this work represents a meaningful contribution to our understanding of the drivers of ice evolution following the LGM. The authors use the model ISSM to simulate Patagonian Ice Sheet evolution in the region which they combine with the TraCE-21ka climate simulation. They use this to: 1) provide constraints on the nature of CLD ice retreat and 2) assess the possible key climatic controls on ice evolution during deglaciation. They provide a detailed methodology and the results of their experiments are clear, highlighting the role of precipitation in modulating ice recession during deglaciation. The authors highlight uncertainties in the model and justify their choices in model setup and design (e.g., GIA, calving).

The authors have been very comprehensive in addressing previous comments on the manuscript. I only have minor comments on the resubmitted manuscript with reference to the methods and results, which are clear from my viewpoint. The discussion in relation to climate is also clear. The majority of weaknesses that remain relate to the discussion, where the descriptions, interpretations, and comparisons to empirical data need to be re-phrased or clarified- some points just do not make sense (e.g., discussion and limitations). I have provided directions for the authors in relation to those. Once these minor corrections are complete (which shouldn't take the authors long at all) I recommend this work, which represents a substantial contribution to our understanding of glacier-climate interactions in the CLD, be published.

Comments on the Manuscript

Introduction:

Line 51: '...across an area presently known as the Chilean Lake District'- add latitude and longitude for CLD area here. This is helpful context, particularly as you are later comparing to the SWW.

Lines 57/58: + and outwash plains, though I think a lot of constraints in this region are also from sedimentological work on exposures, whereas constraints in the east of the CLD are extremely lacking. Maybe add '**only**... well constrained'.

Line 59/60" I had to read this a few times as you have just said the LGM limits are well constrained in the SW/W, maybe add: '... due to a lack of geomorphological and geochronological constraints on ice-margin change **following the LGM**, the reconstructed deglaciation remains highly uncertain'.

Line 63/65: Maybe best to throw a line explaining the Southern Annular mode in this paragraph here? Not everyone will be familiar with regional + SH climate(drivers).

Methods/Results:

The methods and results of this work have been outlined very clearly and resolved in previous iterations, and are combined with a very detailed supplemental document. Just a few clarifications here:

Line 234: 'We simulate calving where the PIS interacts with ocean.' -but not with lakes, add brief sentence so this is clear early on?- I know this is justified later, but here I wondered why it wasn't included given substantial numbers of lakes across the 'Chilean Lake District'.

Lines 330-333: What do you mean by deglaciation? Significant re-advances would imply a punctuated net retreat, versus small glacier fluctuations we would expect to see on an annual basis as a result of seasonal differences in mass balance? Maybe just define what you mean by deglaciation here, as interpretations do vary.

Discussion:

Lines 440-441: '...as limitations in paleo-proxy data and disagreement between climate models prohibit certainty'- '...due to disagreement between paleo-proxy data and climate models'? Or something like this, I struggled to follow.

Lines 443-444: '...linking the paleoclimate change in SWW position and strength from regional paleoclimate proxies remains problematic (Kohfeld et al., 2013).'- again, this was hard to read. What do you mean, re-phrase?

The comparison to climate is detailed, but the discussion of ice retreat and the limitations section can definitely be built upon:

Line 552: Particularly in the CLD- as you have highlighted?

Lines 559-560: Across the CLD, the LGM ice extent is well constrained by geologic proxies particularly in the west and southwest- clarify the timeframe from the panels in Figure 1.

Lines 560-563: 'The moraines that constrain the piedmont ice lobes that formed along the western boundary are now presently lakes and have reasonable age control (Denton et al., 1999; Moreno et al., 1999; Lowell et al., 1995), giving confidence to the LGM ice margin limits.'- How can moraines be lakes? I know what you are trying to say, but this needs re-writing. These north-western outlet glaciers deposited moraines that lay west of the overdeepenings that are occupied by modern lakes. Clarify.

Lines 571-572: '...cosmogenic nuclide surface exposure date retrieved from the Nahel Huapi moraine yielded an age of ~31.4 ka (Zech et al., 2017).'- Where is this moraine? Is it on a figure? We need some idea where it is, even coordinates or a dot on a map somewhere.

Lines 578-581: 'In regards to ice area and extent, our simulated ice sheet at the LGM using TraCE-21ka climate boundary conditions agrees well with the PATICE reconstruction (Figure 10). Our simulations reveal that deglaciation began between 19 ka to 18 ka, consistent with

the geologic proxies (Davies et al., 2020)'. - Can we add a line or two of comparison down the PIS as this is your discussion? This is similar to the Lago Palena/General Vintter (Soteres et al., 2022), Corcovado (Leger et al., 2021, QSR) and Cisnes (Garcia et al, 2019) glaciers southeast of the CLD (~43-44 deg S). Is it different to what is going on even further South (LGC/BA or Tierra Del Fuego)? Or on Isla Chiloe? Worth a mention at least of similarities and differences along the transect of the Andes here. (Note that this is a different Leger paper to the one you mention, same year).

Lines 584-585: 'After 15 ka, mountain glaciers remain in our simulation but there is no presence of a large ice cap as reconstructed in PATICE'- there is no data really at all for this time slice in PATICE. I think you can highlight this at various points here, more data is needed in the CLD to better evaluate this and future models. You have done what you can to evaluate this with available empirical data.

Line 588: '...region largely retreated by 15 ka, with only mountain glaciers remaining.' There is support for this further south. E.g., ice had receded enough for Atlantic-Pacific drainage routes to open east (and drainage reversed) by at around ~16.3 ka (e.g., Leger et al., 2021; QSR; ~44 Deg S)- which supports that the ice sheet had begun to unzip back into smaller ice caps as you show here. Would this not also support the same occurring further north (or even earlier possibly) in the CLD?

Lines 594-595: 'This potential for a favourable and prolonged period of glacier growth is likely missing in our simulations during the ACR, which may explain some of the mismatch against the PATICE reconstruction at 15 ka – 13 ka'. I realise you have a short ACR, but there are not constraints on these time slices in PATICE. You can probably remove or re-phrase this, and highlight that the mismatch is hard to assess due to data paucity here. This is generally a Patagonia-wide issue (we need more constraints).

Limitations section of Discussion:

There are a few points when referring to the geomorphology that this section is a little muddled- here are a few (minor) points to clarify:

Line 616: Re. evidence- are the moraines not comprised of glacio-tectonised outwash (check paper)? Be specific with the evidence. Just provide the details mentioned in the paper here. 'Moraines formed of glacio-tectonised outwash provide evidence for...'. This is helpful context (and it will keep the geomorphologists happy).

Lines 617-619: 'The formation of ice-contact proglacial lakes likely occurred as a function of deglacial warming and ice retreat (Bentley, 1996)'. Well, kind of, but really it is due to mass loss combined with the underlying bed topography (restricting proglacial drainage). Not all glaciers have lakes, it is a product of retreating into their overdeepenings where meltwater becomes trapped. Re-phrase? E.g., examples outlined in recent papers by Dave Evans (Iceland).

Lines 620-624: This doesn't really make sense: 'During deglaciation, iceberg calving into the proglacial lakes may have occurred (Bentley 1996,1997; Davies et al., 2020), with evidence suggesting that local topography and calving may have controlled the spatially irregular timing of abandonment from the terminal moraines surrounding the proglacial lakes (Bentley, 1997).

- 1) If you have an ice-contact lake, you have calving in the ablation area... re. '...iceberg calving into the proglacial lakes may have occurred'. This is not necessary; remove or re-phrase point.
- 2) Surely calving cannot control the glacier abandonment of the terminal moraine positions surrounding the proglacial lakes, because the glaciers had not yet developed lake? Am I missing something? Please clarify/re-write this point so that it is clear.

Lines 627-629: 'However, across our region, Heirman et al. (2011) indicate that it is not well constrained how the proglacial lakes in the CLD may have influenced local deglaciation, as more geomorphic data is needed'. It's true that we do not have geomorphological data, but a lot is probably at the base of these lakes (if at all) and would require bathymetric surveys. There has been some work done on glaciolacustrine varve sediments around Lago Buenos Aires (see: Bendle et al., 2017/2019 (?) papers) supports a period of rapid recession following the onset of calving as glaciers retreated and formed lakes in their overdeepenings. Maybe reference some of this work? It builds on these points.

Conclusions:

- If you add these additional comparisons to the discussion, can we feed a line or two in here summarising the key points?

Figures:

Figure 1: Generally, I would make sure that maps have a north arrow, scale bar, and grid (latitude/longitude). Not necessary for all panels, but at least one to provide context.

Figure 5: I am struggling to follow this description. Is it not dark blue where ice is persisting after 10 ka? Is something wrong here either in the caption or the figure? Please clarify and fix if needed.

I hope that my comments are of some use to you and I look forward to seeing this published in the near future.