Climate of the Past Discussions

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Review of "Atmosphere-cryosphere interactions at 21 ka BP in the European Alps" by Del Gobbo and al.

Julien Seguinot (Referee)

Referee comment on "Atmosphere–cryosphere interactions during the last phase of the Last Glacial Maximum (21 ka) in the European Alps" by Costanza Del Gobbo et al., Clim. Past Discuss., https://doi.org/10.5194/cp-2022-43-RC2, 2022

Dear editor, dear authors,

I am writing this review with the perspective of a glaciologist and hence with limited knowledge of atmospheric circulation modelling, but much interest in the results presented here. Due to my background it is difficult for me to comment on the atmospheric modelling and bias correction methods, the latter of which I understand to have an important effect on presented precipitation fields and parametric equilibrium line altitude (ELA) reconstructions. My comments below are probably biased towards glaciology and paleoglaciology, but I hope they serve as an opportunity to increase the interdisciplinary outreach of the study.

Glaciers and ice sheets are sensitive climate indicators, but because they typically incept on mountains, they are sensitive to local mountain climates which are difficult to resolve in climate observations and models. Hence highly-resolved regional climate simulations over glaciated regions are very valuable, particularly for glacial periods for which there is much fewer output available than for the present-day. This is exactly what the study by Del Gobbo et al. has to offer, and therefore I strongly support publication of the paper and data. However, I also find that parts of the methodology are unclear, and some of the conclusions very far-fetched, particularly for the second part of the study where the authors use modelled climate averages to reconstruct an "environmental" ELA based on a simple parametrization and find "excellent consistency with Alpine glacier reconstructions" with little consideration for glacier mass balance above and below the ELA or glacier flow dynamics. I think this obfuscates the more robust (and more interesting in my opinion) parts of the study on temperature, precipitation and wind conditions over the Alps during the LGM. This said, I really appreciate the authors efforts to reach a wider interdisciplinary audience, and I hope that my criticism here is constructive and not destructive.

General comments

Time scope

The paper opens on an accurate and well-referred introduction to the Last Glacial Maximum (LGM) as a complex period lasting several thousands of years with glaciers reaching peak extension at different ages both globally ("26.5 to 19 ka BP") and within the Alps ("26.5 to 23 ka"). However, the rest of the manuscript uses "at the LGM" making it unclear which time period is referred to exactly within this range, except for the title including "21 ka". I imagine that simplifications had to be made here to build the study on available datasets and global simulations, but these need to be acknowledged and discussed in the paper. Here are changes that I suggest.

- In the intro, explain which time period or interval is targeted by the study. Is this "26.5 to 23 ka" as suggested by the intro or "21 ka" as suggested by the title?
- In the methods, explain which age is represented by orbital parameters and greenhouse gas concentrations used in the global simulation, which ice sheet reconstruction is used in the global simulation, and which period is represented by Ehlers et al. (2011).
- In the discussion, address the resulting time inconsistencies between model inputs, output, and study target period, discuss ways this could affect the results and conclusions,
- Throughout the manuscript replace "at the LGM" to "during the LGM" or "at 21 ka" as depending what is referred to exactly.

Surface topography

The manuscript does not specify which surface topography data was used in the regional and global atmospheric models. I think this is an important modelling choice that needs to be clarified and discussed. The thickness of the LGM ice sheet has been debated (Imhof et al. 2021). How would a thinner or thicker ice sheet topography affect the modelled precipitation and winds? Another study in CPD (Velasquez et al., 2021) may provide elements of answer.

- Imhof, M., Cohen, D., Seguinot, J., Aschwanden, A., Funk, M., & Jouvet, G. (2019). Modelling a paleo valley glacier network using a hybrid model: An assessment with a Stokes ice flow model. Journal of Glaciology, 65(254), 1000-1010. doi:10.1017/jog.2019.77
- Velasquez, P., Messmer, M., and Raible, C. C.: The Role of Ice-Sheet Topography in the Alpine Hydro-Climate at Glacial Times, Clim. Past Discuss. [preprint], https://doi.org/10.5194/cp-2021-67, in review, 2021.

Assumption of steady state

The assumption that glaciers are at a steady-state need to be further discussed. While glaciers on the south slope of the Alps were confined to a steep topographic and climatic gradient, glaciers on the north slope took thousands of years to develop and reach their maximum extent lagging behind climate change (Seguinot et al. 2018). The maximum LGM extent in particular is very likely to be a transient stage where glaciers had more room to extent northwards into cold continental climate (also supported by sub-zero annual temperatures in the present study) had the coldest climate lasted longer. The ice sheet configuration at 21 ka is less well known but there is a possibility that Alpine glaciers were closer to equilibrium then, as the geology indicates that they remained large (albeit smaller than LGM) for several thousands of years (Wirsig et al., 2016).

Comparison to glacier extent

Besides climatic variables (temperature, precipitation and wind), parametric glacier Equilibrium Line Altitude (ELA) reconstructions are presented as a major output used to validate the model results. This validation is based on comparing the results with local moraine-based ELA reconstructions, and the Alpine-wide ice sheet reconstruction. However, direct comparison between ELA and glacier extent means bypassing two important disciplines of glaciology: glacier surface mass balance (only partly represented by the ELA) and glacier dynamics (ice flow due to gravity). In the current version of the manuscript it is unclear which criteria is used to claim "excellent consistency [between ELA and] Alpine glacier reconstructions", and I find this part of the discussion and conclusions very far-fetched.

ELA changes are a useful indicator for mass balance for small glaciers, but for an ice sheet as in the LGM Alps, strong melt near the termini (mostly temperature-dependent) and high accumulation on ice divides (mostly precipitation-dependent) are significant contributors to mass balance not captured by ELA changes. On the other hand, comparisons between the parametrized ELA and previous ELA reconstructions make a lot more sense, because they are based on studies including ice dynamics, albeit in a simplified way and usually assuming steady-state.

Supplementary data

As reviewer I could access a limited auxiliary dataset consisting of annual precipitation, annual, summer and winter mean surface temperature, and parametrized ELA grids, as well as glacier catchment wind and precipitation time-series from Dec. 1, 1930 to Nov. 30th, 1949 (there is probably a mistake in the date for LGM data). Documentation and metadata is very limited. For instance it is unclear whether the data are bias-corrected.

I really want encourage the authors to put additional effort into publishing their model output in a way that better safeguards its legacy and usability. High-resolution climate simulations such as presented here are expensive and have a high carbon footprint. Regional paleo-climate simulations in particular are rare and very valuable. The data you produced has widespread applications in paleoclimatology, paleoglaciology and paleobiology. There is currently a lot of research going on in the Alps, and such effort is almost guaranteed to pay back in terms of your study's visibility and impact.

My recommendation here (again with glaciological applications in mind) is to include at least the following variables:

- monthly mean temperature,
- monthly mean precipitation,
- monthly standard deviation of daily mean temperature,
- surface topography (important to interpret temperature), and
- bias corrections.

This will allow to run a simple empirical glacial mass-balance (positive degree-day) model going one step further on the ELA estimates presented here, which could also be used to drive an ice sheet model in the future.

Specific comments

Introduction

- l. 60 "The analysis of speleothems sampled in different caves [...] precipitation occurring between spring and autumn [...] intense snowfalls during autumn and early winter." Are these two caves located in different parts of the Alps? How do these observations relate the partitioning and seasonality of precipitation presented in the results?
- l. 73 "simulated temperature and precipitation (Å½ebre et al., 2020; Ohmura and Boettcher, 2018)": I think a few extra words are needed here to explain the method to go from temperature and precipitation to ELA.
- l. 74 You refer alternatively to Å½ebre et al. (2020), Å½ebre (2020) and Å½ebre et al. (2021) but only the latter is included in the reference list.

Methods

- l. 82 "two 20 years time slices": is 20 years also the duration of the regional simulations?
- l. 83 "LGM standard and PI": please define "LGM standard and PI", and spell out "PI".
- l. 92 "2.2 land-use and topography reconstruction": this section only describes the land mask and sea level lowering. Please explain which topographic dataset is used in the regional model.
- l. 114 "averaged over 19 years": how do these 19 years relate to the total simulation length? Is there a spin-up period before that?
- l. 118-119 "we assume that glaciers are at a steady-state": this is an important simplification (see general comment).
- l. 121 "an empirical equation relating mean summer temperature and accumulated annual precipitation": since this equation is central to the second part of the results, I think it would be good to add a short explanation on how it was derived, and the rationale for using it instead of computing glacier mass balance for instance using a positive-degree day model.
- l. 130 "validated for the Alpine region by Å½ebre (2020)": please add a few words here to understand which time period and which type of data have been used for validation.
- l. 131 "2.5 Circulation Weather Type": I think this section corresponds to a single sentence in the results (l. 180-182) and it is unclear to me what it adds to the study. I suggest to either remove this computation from the study, or add a figure showing the results.
- l. 132 "total shear vorticity (Z) and the resultant flow (F)": depending on how you address the previous comment, could you please define these terms for interdisciplinary readership?

Results

- l. 138 "domain of study": I think this section belongs to the methods, not results. This would also be a good place to clarify the time domain.
- l. 141 "greater Alpine region": what is implied by "greater" here? Is the bias-correction domain different from the model domain? Again, this belongs to the methods.
- l. 143 "3.2 The large-scale framework: the MPI-ESM-P simulation": I could not understand whether this section presents new results, or results previously published by Ludwig et al. (2016). The comparison with a previous study probably belongs to the discussion part.
- l. 154 "3.3 RegCM4.7: Atmospheric circulation": this section is very expansive. I suggest to split it into synoptic conditions, temperature, precipitation and winds, corresponding to Figs. 1-4.
- l. 155-167 "a NE-SW pressure gradient", "strong influence of the Siberian high" "cold air descending the Italian peninsula", "deflected eastward over the Tyrrhenian Sea" Without detailed knowledge of the Alpine climate it is difficult to understand how these conditions differ from today. Later parts of the text always explain how modelled LGM conditions differ from the present-day. I suggest you do the same for these two paragraphs.
- Fig. 1 only presents LGM conditions, whereas Figs 2-3 also include pre-industrial and anomaly panels, which I find very useful. Two additional panels showing present-day wind directions would greatly help understanding how these patterns changed during the LGM.
- Figs. 1-3 Are these 19-year averages as in Fig. 4? Please clarify in figure captions.
- l. 161 "All these findings indicate a strong influence of the Siberian high": maybe this belongs to the discussion

- l. 188 "We used daily data from 19 simulated years": I think this information should also appear in the caption of Fig. 4.
- l. 208 "The envELA calculations were performed following the method proposed by Å½ebre et al. (2021) (Eqs. 3, 4, see methods)." The reference year is different from the methods parts.
- l. 216-221 "By comparing the envELA with the model topography" This paragraph belongs to the discussion.
- l. 221 "the RegCM4 cannot capture the multitude of small glaciers present at the PI but can identify the general glaciated area (the western Alps), while at the LGM the larger glacier extension is better captured by the model." -> the model produces climate variables and ELA which is very different from "glaciated area" and "glacier extension".
- l. 227 "Above 1500 m a.s.l. melting is inhibited due to < 0 °C temperature." Are you referring to JJA mean temperature here? If so, this does not have to be the case. Even with mean monthly temperatures below freezing, a glacier could still experience warmer days causing significant melt. Day-to-day and year-to-year temperature variability have an important contribution on melt when temperatures fluctuate around zero (which is why I ask for standard deviation of temperatures in supplementary data).
- l. 227-229 "The LGM rate of melting is reflected by the runoff values, which are maximum in summer over the Alps and in spring and autumn over the piedmont areas." Which runoff values are referred to? Does the study also include a glacier mass-balance or maybe snowpack model? Could these values actually be more informative than ELA reconstructions presented in the figures?

Discussion

- l. 239 "4 Discussion" This is again a rather long block of text, I think subsections would make it easier to understand which parts of the results are discussed.
- l. 240 "First, we emphasize that our model resolution is among the highest found in paleoclimate studies (Ludwig et al., 2021)": this is true, but please also consider the following studies with nested domain resolution up to 2 km, which also include ice-sheet topography (and have their own shortcomings).
  - Velasquez, P., Kaplan, J. O., Messmer, M., Ludwig, P., and Raible, C. C.: The role of land cover in the climate of glacial Europe, Clim. Past, 17, 1161–1180, https://doi.org/10.5194/cp-17-1161-2021, 2021.
  - Velasquez, P., Messmer, M., and Raible, C. C.: A new bias-correction method for precipitation over complex terrain suitable for different climate states: a case study using WRF (version 3.8.1), Geosci. Model Dev., 13, 5007–5027, https://doi.org/10.5194/gmd-13-5007-2020, 2020.
  - Imhof, M. A.: Combined climate-ice flow modelling of the Alpine ice field during the Last Glacial Maximum. VAW-Mitteilungen, 260. https://doi.org/10.3929/ethz-b-000483937, 2021.

- l. 253 "our envELA shows a drop consistent with the geological reconstructions (Ehlers et al., 2011)." please see general comment.
- l. 261 "glacier dynamics [...] e.g. avalanches, wind drifts, dust deposition, or debris fraction": in glaciology "glacier dynamics" usually refers to ice flow due to gravity, whereas these processes affect the glacier surface mass-balance (and are probably less

relevant in this context).

- l. 266 "Our LGM simulation refers to 21 ka BP": this needs to appear earlier.
- l. 269-279 I find this part of the discussion is very far-fetched because it does not consider the very different topography north and south of the Alps and how it affects ice flow, glacier surface mass-balance and response time.
- l. 300 "The decrease in envELA at the LGM compared to PI": I think it would be useful to include the supplementary figure(s) here.
- l. 290-309 "The envELA estimates for the PI (Fig. S2)"
- l. 313-316 "reduced westerly winds as well as increased north-northeasterly winds [...] increased wind activity" To put these statements in context it would be worth to include PI conditions on Fig. 1.

Conclusions

- l. 379 "Our reconstruction matches with geomorphological evidence and resolves for the first time some shortcomings that occurred in previous LGM glacier reconstructions based on ice-flow dynamics." I find this statement very bold considering that your study does not produce an "LGM glacier extent reconstruction". I have no doubt that a highly-resolved climate dataset for the LGM Alps is very valuable and very useful for future glacier mass-balance and glacier modelling (and much more). But in my opinion such steps are necessary before asserting that your climate dataset "matches with geomorphological evidence" from glaciers.

Technical corrections

- Many abbreviations are used, some of which are not spelled out. Please make sure that every abbreviation in the text is defined.
- l. 27 "ice-stream network": *Eisstromnetzwerk* has been used in German Alpine literature and sometime literally translated, but in English literature "ice-stream" typically describes the low-topography, fast-flowing regions of continental (esp. Antarctic and Laurentide) ice sheets.
- l. 47 "North American Ice Sheet": in paleoglaciology we usually refer to "North American ice sheets" or "ice sheet complex", including the Laurentide, Cordilleran, Innuitian and sometime Greenland, ice sheets, which only collided during glacial maxima.
- l. 67 "Therefore, here" I suggest to break the paragraph here, (and maybe remove "therefore"), before the content of this study are announced.
- l. 75 "LGM glacier mass balance": change to "LGM ELA".
- l. 123 Eqn. 3. Units for the constants are missing.
- Figs. 1-3 is summer / winter (Fig. 1) the same as JJA / DJF (Fig. 2)?
- Fig. 3: there is probably a mistake in precipitation units or values, even Bergen is not that rainy!

- l. 165 "pver" -> "over".
- l. 187 "four Alpine piedmont glaciers" -> "four subdomains corresponding to LGM Alpine piedmont glaciers"
- l. 192 "more events" -> "more precipitation events"
- l. 311 "alpine" -> "Alpine"
- l. 379 "coditions" -> "conditions"
- l. 383 "agreemtn" -> "agreement"

I hope you can make good use of my comments and look forward to a future version of your article.

With best regards,

Julien Seguinot.