Dear Editor,

On behalf of my co-authors, I am writing to resubmit our paper originally entitled *“Atmosphere-cryosphere interactions at 21 ka BP in the European Alps”* and now entitled” *“Atmosphere-cryosphere interactions during the last phase of the LGM (21 ka BP) in the European Alps”* (research article CP-2022-43) to Climate of the Past.

We would like to thank you and the reviewers for the constructive comments on our manuscript. We believe your feedback has helped us to substantially improve our work.

We have revised our manuscript according to the reviewers comments and we attach the following files:

- the manuscript with the changes highlighted using track change;
- point-by-point responses to the reviewer comments, where the reviewer comments are in red font and our responses follow an “A:”;
- a clean version of the manuscript and the supplementary material.

In particular, as you and reviewer 1 requested, we have expanded the description of the method we used to calculate the environmental ELA (paragraph 2.5) and we added a figure (new Fig. S1) which we believe can help in the understanding of the equations.
Furthermore, in accordance with your request, we have rewritten several parts of the discussions and split them into five sub-paragraphs. In this way, we have better illustrated the limits of our approach as well as the match between the geological evidence and our model results, limiting the comparison with glaciological models.

The new version of the manuscript also shows minor corrections for typos, updated affiliations, some new references, new figures (new Figs. S1, S5 and S6) and new variable names in Eqs. 3 and 4. The new version of our dataset, that we agree to make public, can be found at the DOI: 10.5281/zenodo.727846.

All authors have approved the revised manuscript.
We look forward to hearing from you,
Sincerely,

Costanza Del Gobbo

Costanza Del Gobbo

Reply on RC1

This paper presents a new regional climate model (RCM) of the European Alps during the Last Glacial Maximum (LGM, about 21'000 years ago) at a resolution of 12 km. Based on the new RCM, the authors revisit the cryospheric LGM state in terms of glacier extent. The goal here is to use climate modelling to investigate former glaciations in the Alps and complete our knowledge based on geological findings (e.g. based on the analysis of landforms such as moraines). The LGM precipitation pattern inferred by the authors is valuable to understand the global atmospheric circulation prevailing in the Northern Hemisphere during the LGM as it was hypothesized that the shift of the polar front (due to the presence of massive ice sheets over the American continent) must have changed storm track trajectories, and modified dominant moisture advection over the Alps, with substantial impacts on the building of glaciers in the Alps (e.g., Luetscher and al., 2015). The link between precipitation pattern (and more generally the entire climate dataset) and geologically-based glacier reconstructions is analyzed and discussed in the paper.

Climate modeling has a great potential to improve our understanding of climates of the past -- during key periods such as the LGM -- and their impact in terms of glaciations. This potential has hardly been explored to date. Therefore, I believe this study is a valuable and original contribution in the field. Overall, I found the paper interesting, well-structured and well-written (despite several typos). As I'm not a climate scientist, I can hardly judge on the methodology to infer climate. Therefore, my comments -- listed below sorted by decreasing importance -- are focused on the glaciological analysis. My main concern is about the comparison of the inferred environmental ELA to geologically-reconstructed glacier outline, which currently does not evidence a significant fit I think. Similarly, there are statements in the text that are not (or hardly not) supported by clear evidence in Figure/results. Lastly, I think the authors should discuss the limitations of the environmental ELA method that infer glacier information from climate, as the approach is highly simplified regarding the complexity of glacier processes. I hope that my comments help the authors improve the manuscript.

Main Comments

- Section 2.4, the computation of the envELA is obscure to me, it should be clear without having to go to the paper from Zebre and al. (2020).(e.g. say clearly that envELA is the theoretical altitude where glaciers can be sustained; I had to go to Zebre and al. (2020) to find it, or maybe I missed it.)

A: We extended the paragraph that introduces the envELA and the method we used to calculate it:

- in the introduction: “More precisely, the ELA is defined as the spatially averaged altitude of the set of points on the surface of the glacier where the ice mass balance is zero at a given time (Cogley et al. 2011). When the ELA is inferred at a regional scale without considering the effects of the morphology of the surface (i.e. shading, avalanching, snow drifting, glacier geometry or debris-cover) and it is averaged over at least some decades, it is called environmental ELA (envELA) which represents the theoretical altitude where a glacier can form and be sustained in a region (Anderson et al., 2018). Therefore, changes in ELA are especially powerful indicators of climate-glacier interactions. Here, we estimate the envELA of Alpine glaciers at 21 ka BP and pre-industrial (PI) times following the methodology developed by Žebre et al. (2020). We calculate the envELA using a simple parametric equation based on the theory of mass and energy conservation, which relates simulated summer temperature and annual precipitation (Ohmura and Boettcher, 2018) disregarding the local topographic effects acting on glaciers. An advantage of this method is that it does not require elaborate input datasets as in more sophisticated approaches which include the glacier dynamics driven by mass balance processes (e.g., Huss and Hock 2016; Zekollari et al., 2020)"

- In the methods (2.5 Environmental Equilibrium Line Altitude): "The envELA is calculated following an inverse approach based on bias corrected annual precipitation and summer temperature (Eqs. 1 and 2) and is averaged over the 19 years of the model simulations, since we assume that glaciers are at a steady-state during the simulation time. The calculation uses the methodology adopted by Žebre et al. (2020) which is based on an empirical equation relating mean summer temperature and accumulated annual precipitation at the envELA. This equation relates glacier and climate conditions; it was first introduced by Ahlmann (1924) in the form of a precipitation/temperature diagram (P/T diagram) and then recently updated by Ohmura and Boettcher (2018) using temperature, precipitation and solar radiation data from 104 glaciers worldwide. The P/T curve can be approximated by a quadratic function and is based on the principles of mass and energy conservation "

- I understand Eq. (4), but why do we need Eq. (3)?

A: Eq. 3 is used to derive the temperature (T_{ELA}) that we use in Eq. 4. Eq. 3 represents the P/T diagram of Ohmura and Boettcher (2018) and is the basis of the method we apply.

- The RCM gives mean summer temperatures, so I don't understand why you need to compute it via (3).

A: The RCM give us temperature and precipitation (T_{corr19} and P_{corr19}) at the model topography. We need to compute the temperature, via eq. 3, at the envELA level. We assume that only temperature varies vertically but not the precipitation.

We added a supplementary figure (new Fig. S1) and extended the explanation of the method we used to calculate the envELA in the methods (2.5 Environmental Equilibrium Line Altitude): "Eq. 3, representing the P/T diagram, is solved for T_{ELA}, using P_{corr19}, which is the RegCM bias-corrected accumulated annual precipitation averaged over the 19 years. Proceeding with an inverse approach, we assume that only precipitation (P_{corr19}) refers to the envELA level, but not temperature. Then, we use bias-corrected RegCM precipitation (P_{corr19}), assumed at the envELA, to calculate with Eq. 3 the envELA temperature (T_{ELA}). Subsequently, we convert the temperature difference between the envELA and the topography (T_{ELA} - T_{corr19}) into an altitude difference, using an environmental lapse rate of 0.65°C/100m. Finally, the resulting elevation difference is subtracted from the topography (DEM) in order to obtain the envELA for every grid-cell (Fig. S1)"

- Another very important point is: what is the DEM you use? is it present topography or a LGM reconstruction of the surface (including glaciers)? This is crucial missing information.

A: We added explanations:

- about the topography used for the simulations in paragraph 2.3. “First, for LGM conditions we modified the present-day model topography (GMTED2010; Danielson and Gesch, 2011) and bathymetry (ETOPO1; Amante and Eakins, 2009) by decreasing the sea level by 120 m (Peltier and Fairbanks, 2006), and changed the land sea-mask in order to account for the corresponding variation of the coastline. The resulting dataset was then interpolated by the RegCM4 preprocessor tool onto the desired grids at 12 and 50 km. This caused a smoothing of the topography that in particular affected the smallest orographic features, such as mountain tops and narrow valleys.”
- about the ice thickness in paragraph 2.3. “Finally, we added a two-dimensional representation of the LGM glaciers based on Ehlers et al. (2011). Because of the topography smoothing and the relatively coarse RegCM4 resolution, the Alpine glacier thickness is not considered in the topography representation, although Merz et al. (2015), Imhof (2019) and Velasques et al. (2022) highlighted the importance of including glaciers’ topography into global and regional paleoclimate models.”
- and about the topography related to envELA calculations in paragraph 2.5. “The reference topography for the 21 ka BP and PI envELA calculations is the PI topography, after the application of a correction accounting for the 120 m of elevation difference between the two periods due to the sea level decrease. This facilitates the comparison of the envELA datasets for the two periods and with the ELA values obtained from geomorphological reconstructions. The envELA computations for both the 21 ka BP and the PI are performed using three different topographies, the RegCM4, the HISTALP, and LAPrec ones. The three resulting envELA datasets are then averaged. Because the observational and simulated datasets do not use the same horizontal grid, we remapped the RegCM4 and LAPrec data onto the HISTALP 5 arcmin resolution grid.”
- l216 to l221 and Figure 5: you argue that you can assess your modeled climate against the reconstructed glacier outline by comparing the envELA with the model topography.I agree with this. However, I do not see any convincing figure that supports it because only the envELA is displayed in Fig 5, and never the model topography. Also, it is not clear to me what topography you compare -- I assume the LGM topography. Also I found that displaying the colors of the ELA only within the mask derived from Ehlers and al. (2011) is misleading, as it gives the wrong feeling of a fit. Why don't you simply draw the contour of envELA minus LGM DEM (they exist geologically-based reconstructions, e.g. in Switzerland by Bini and al (2009)), and compare the zero-level line to the maximum glacier extent of Ehlers and al. (2011)? An important issue with this paragraph is the lack of supporting figure. I encourage the authors to go over all the statements of the discussion, and to make sure that all of them refer to Figure, Table, or papers.

A: We added two new figures (Figs. S5 and S6) showing the PI and LGM envELA only for those grid-cells where envELA < topography. Although we believe that these new figures facilitate the understanding of the model performance, we also think that Fig. 5 supports other aspects of our reasoning, thus we propose both versions of the figures in the text and supplementary material. With the new figures the wrong feeling of a fit should be resolved.

Concerning the topography, we added an explanation about it in paragraph 2.5 of the methods (see last point of the previous comment). The reference topography for 21 ka BP and PI envELA is the PI topography, after the application of a correction that accounts for the 120 m of elevation difference between the two periods due to the difference in sea level.

- Following my previous comment, I think that comparisons between your model results to geologically-based reconstructions (e.g. from Ehlers and al. (2011)) is way more important than comparison with modeling studies based on the Parallel Ice Sheet Model (PISM) from Becker and al. (2016) or Seguinot and al. (2018). Indeed, it is far from obvious to compare your results to the one from PISM as i) your climate forcing is very different and more funded than the simple distortion of present-day climate used in PISM studies ii) PISM is very different and more funded to compute the glacier response from a climate than the environmental ELA. Therefore, it is difficult to distinguish which from i) or ii) is mainly responsible for discrepancy between your results and the PISM-based ones. Instead, I would encourage the authors to focus further on comparisons with purely geologically-based reconstructions.

A: We rearranged the text to reduce the importance of the comparison with the studies based on PISM (paragraph 4.1) and to highlight the geologically based reconstructions (paragraph 4.4). We also modified Fig. 5 by removing the red line which was referring to the work of Seguinot et al. (2018).

- l242-247: This statement is not supported by any figure or table of the paper.

A: We did not provide a figure/table here because the focus of the validation is on the comparison between our envELA and the geological-based reconstructions (paragraph 4.4).

- l 254: "where our envELA shows a drop consistent with the geological reconstruction": again this statement is not supported, or if I missed it, you should clearly indicate what figure you are referring, and ideally, make sure the caption permits to link the statement to evidence on the figure.

A: The reference is the Fig. 5, as now indicated.

- Unless I missed it, I see no or very little discussion on the limitation of your approach to interpret climate data into glacier information. Yet, the inference of the envELA, and its interpretation in terms of glacier coverage, relies on strong assumptions such as ignoring dynamical and transient aspects of climate and glaciers. Just one example: Knowing the LGM climate is important, but the duration of the latter has prevailed is equally important for shaping glacier: For example, under the same climate, Rhone Glacier would need a longer time period to reach its known LGM extent than Rhine Glacier because the latter is smaller (in term of drainage basin) and has less inertia. Therefore, the transient aspect of climate is also very important to explain glacier footprints. Of course, this cannot be evidenced with the steady-state assumption. But this illustrates why elaborating further on the limitation of your method is needed I think.

A: We added a paragraph (4.2) in the methods where the limitations of our approach are discussed.

Minor comments

- Title: suggest writing Last Glacial Maximum instead of 21 ka BP \item

A: New title: Atmosphere-cryosphere interactions during the last phase of the LGM (21 ka BP) in the European Alps

- Abstract: Second sentence: suggest changing "affected" by "controlled"

A: ok

- Abstract: Third sentence: "physical processes" may be overstated as the interpretation of the climate in terms of glacier extent lacks number of glacial processes (e.g. transiency/dynamical aspects), consider rephrasing.

A: We reformulated “some of the physical processes sustaining the Alpine glaciers extent during the last phase of the LGM, at 21 ka BP.”

- l 23:... is considered \textbf{to be} a global event ...

A: ok

- l 27: "ice stream" usually refers to fast flow ice, not sure this is appropriate here.

A: “Ice stream network” was replaced with “interconnected valley glaciers”

- l 31, north and \textbf{west} (Rhone, Lyon) \item

A: ok

- l 39: mountain glaciers \textbf{worldwide} ...

A: ok

- l 42: 3 to 6 sounds not much. Augmenting the literature will enlarge the range. For example, you may include the paper by Tierney and al. 2020 in Nature (Glacial cooling and climate sensitivity revisited).

A: We added references (Schmittner et al.,2011; Annan and Hargreaves, 2013; Snyder, 2016; Tierney et al., 2020) and enlarged the temperature interval to “1.7 to 8.2 °C °C lower than in present conditions”

- l 58 "widely studied" calls for references

A: We added references (e.g., Beker et al., 2016; Ludwig et al., 2016; Kuhlemann et al., 2008; Florineth and Schlüchter, 2000)

- l 74: there is something strange with the citation (Zebre et al. 2020), please fix it.

A: Žebre et al. (2020) is correct, but we fixed in other parts of the text, where it was wrong

- l 83: I don't think you have introduced the acronym PI before, I assume it is Pre-Industrial?

A: PI is now defined in the abstract and in the last paragraph of the introduction

- section 3.3, title, add this is the Regional model

A: Ok (now it is section 3.2) “3.2 Regional Climate Model RegCM4.7: Atmospheric circulation”

- It would help to have a figure showing the result of the large-scale climate simulation (section 3.2), e.g. to visualize the 9°C cooling or -30% reduction of precipitation.

A: The analysis of the MPI-ESM-P model is beyond the scope of this work, thus we preferer not to include this figure as it would not refer to our simulations, although also the GCM simulations were validated before using them to force our RCM. An extensive validation of the MPI-ESM-P has already been performed in other studies (e.g., Ludwig et al., 2016).

- l 190: "the two glaciers are mainly \textbf{interested}..." is a strange formulation

A: Changed “interested” with “affected”

- l 209: PI ELA at 2435 m sounds low to me, what does the literature say?

A: The comparison with the literature is presented in the discussion section, in what is now paragraph 4.4. “The envELA estimates for the PI (Fig. S3) can be compared with different studies of the Little Ice Age (LIA). For example, Colucci (2016) placed the ELA in the Julian Alps at 2275 m a.s.l. for the Canin glacier and at 2486 m a.s.l. for the Triglav glacier, while our results yield lower values of 1750-2000 m a.s.l. The ELA in the Ecrins group and Maritime Alps has been estimated at 3000-3100 m a.s.l. and 2841-2818 m a.s.l. respectively (Federici et al., 2017; Cossart et al., 2012), in agreement with our results of 2750-3000 m a.s.l.. Our estimate for the envELA in the Val Viola area, Central Italian Alps, is in the range of 2500-2750 m a.s.l., while Scotti et al. (2017) place it at 2815-2850 m a.s.l..”

The value of 2435 m is averaged over the whole Alpine chain, for which we do not have a direct comparison in the literature. However, by analysing different Alpine sectors for which ELA reconstructions exist, we see that for example in the eastern Alps the PI envELA is somewhat lower than the geomorphological data, but generally there is a resonable match. Also, the envELA drop we produce is consistent with the other studies (Federici et al., 2017 and Ivy-Ochs et al., 2006) as well as the LGM envELA values.

- l249 in a previous study: you may cite Visnjevic and al. (2020).

A: Ok, added also Becker et al. (2016), Jouvet et al. (2017), Seguinot et al. (2018)

- l 270: what is this (8)?

A: Kelly et al., 2004

- l 280: Baker is Becker, please correct everywhere in the text.

A: Ok, corrected

- l 361: some discrepancies: can you be more specific? what discrepancy? what study?

A: This statement belongs to a paragraph that was moved to the conclusion and rephrased (see next comment). However, the studies we name are for example Seguinot et al. (2018) and Beker et al., (2016) and were analysed in the discussions.

- l 361-369: looks like a conclusion

A: We agree and moved this paragraph to the conclusions.

- l 379: typo, remove the space before the dot.

A: Ok, corrected

- l 383: typo; agreement

A: Ok, corrected

Reply on RC2

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?

A: In the introduction we added a paragraph to explain the time period defined as LGM and we also modified the title. "In this regard, in order to be consistent with the periods of available MPI-ESM-P fields providing the initial and boundary conditions to run our RCM, here the simulated LGM corresponds to 21 ka BP, the last phase of the actual LGM, which is considered the standard in paleoclimate modelling according to the PMIP3 protocol (Braconnot et al., 2012)."

- 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).

A: We added a paragraph in section 2.1 "The greenhouse gas (GHG) concentrations used in both the global and regional simulations are compliant with the CMIP5/PMIP3 protocol (Braconnot et al., 2012) for 21 ka BP and the PI conditions. The MPI-ESM-P uses orbital parameters and ice-sheet reconstruction from the same protocol, while the orbital parameters for the RegCM4 are calculated following the equation proposed by Berger (1978).".

We specified that Ehlers et al. (2011) represent the LGM in section 2.3.

- 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,

A: We expanded the discussion we provided in the first version of the manuscript. "Our LGM simulation refers to 21 ka BP. This time does not correspond to the maximum glacier extention during the LGM, which occurred between 26.5 and 23 ka BP, although individual Alpine glaciers reached their maximum extent and started their retreat at different times in different sectors (Monegato et al., 2017; Seguinot et al., 2018). Because at 21 ka BP the withdrawal of the Alpine glacier had not yet started we assume that 21 ka BP is a good approximation for average conditions during the LGM. In particular, radiocarbon and cosmogenic isotope datings (Ivy-Ochs et al., 2022; Kamleitner et al., 2022) show a late retreat (~18 ka) for some glaciers in the southern Alps (Garda and Ticino), for which our calculations indicate a low envELA (Fig. 5), while the Dora Riparia, Dora Baltea, Piave and Tagliamento glaciers started withdrawing earlier."

- Throughout the manuscript replace "at the LGM" to "during the LGM" or "at 21 ka" as depending what is referred to exactly.

A: ok

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.

A: We added more details about surface topography:

- about the topography used for the simulations in paragraph 2.3. “First, for **L**GM conditions we modified the present-day model topography (GMTED2010; Danielson and Gesch, 2011) and bathymetry (ETOPO1; Amante and Eakins, 2009) by decreasing the sea level by 120 m (Peltier and Fairbanks, 2006), and changed the land sea-mask in order to account for the corresponding variation of the coastline. The resulting dataset was then interpolated by the RegCM4 preprocessor tool onto the desired grids at 12 and 50 km. This caused a smoothing of the topography that in particular affected the smallest orographic features, such as mountain tops and narrow valleys.”
- about the ice thickness in paragraph 2.3 “Finally, we added a two-dimensional representation of the LGM glaciers based on Ehlers et al. (2011). Because of the topography smoothing and the relatively coarse RegCM4 resolution, the Alpine glacier thickness is not considered in the topography representation, although Merz et al. (2015), Imhof (2019) and Velasques et al. (2022) highlighted the importance of including glaciers’ topography into global and regional paleoclimate models.”.

Consideration about this choice is presented in the discussion (4.2): "A possible uncertainty in our results is related to the model resolution and glacier thickness. In particular, the latter can modify not only the temperature patterns but also precipitation and wind fields. Due to the topography smoothing in the RegCM4 and the model relatively coarse resolution we did not include ice thickness in the simulations. However, where the valleys are larger (Garda and Rhône) this might introduce some uncertainty in the envELA estimations."

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).

A: Even though atmosphere and glaciers are transient systems, the analysis was performed by considering them at a steady-state as a 20-years-long simulation represent a short interval in the longer temporal framework of the LGM and of the glacier evolution.

These considerations were expressed

- in the methods (section 2.1): "Note that, even though the atmosphere and glaciers are transient systems, a 20-year-long simulation represents a relatively short interval within the longer temporal framework of the LGM and of the evolution of extended glaciers, and therefore the analysis assumes steady state conditions."
- and in the discussion (section 4.2): "As we are interested in the climate fields, the steady state assumption and the ELA averaging over the whole simulation time masks the effects of outlier anomalous years. Indeed, as shown by Žebre et al. (2020), a year-by-year envELA computation would reflect these events. Conversely, the effective ELA does not react quickly to extreme events, being the result of snow accumulation and metamorphism also from previous years. In this framework, the envELA averaged over the 19-years of our simulations can provide a more reliable estimation of the effective ELA in terms of absolute values and temporal evolution. In fact, Žebre et al. (2020) pointed out that the envELA averaged over a long climate period shows a good match with the effective ELA of glaciers particularly susceptible to avalanches and wind-blow snow. Thus, the steady-state assumption enables us to at least reduce part of the deviation between effective and environmental ELA. On the other hand, the steady-state assumption implies that the dynamical and transient aspects of climate-glaciers interactions are overlooked.".

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.

A: This was added to the discussion (section 4.1). “Despite the different time responses of envELA and glacier extention to changes in climate, since the envELA is directly related to temperature and precipitation while the glacier extention has a lag due to ice dynamics, according to Žebre et al. (2020) the envELA variations can be associated with variations of the front position and the effective ELA of glaciers (i.e. the ELA calculated from geodetic or direct glaciological mass balance measurements). Also, the envELA calculations allow a more detailed discussion of local differences in the geological reconstructions over the Alpine region.”

- 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.

A: There is evidence that at the LGM the Alps were interested by a network of valley glaciers descending from some ice domes in the western Alps, which behave differently than an ice sheet. However, the method that we use clearly do not consider detailed mass-balance processes and ice rheology.

We compared the envELA with geological reconstructions (paragraph 4.4), and when they were not available, we discussed our results in relation with other model studies of glacier extent.

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.

A: We agree to make the data available. The metadata have been expanded. The dates are model dates and not real ones. The information about the bias-correction is now present in the metadata and the documentation on the zenodo page.

The dataset is comprehensive of:

- monthly mean temperature, precipitation (21 ka BP and PI) and topography at a resolution of 12 km;
- bias-corrected monthly mean temperature, precipitation (21 ka BP and PI) and topography remapped over the HISTALP dataset (Auer, 2007);
- envELA, calculated according to Žebre et al. (2020) for 21 ka BP and PI;
- daily wind direction and precipitation for 21 ka BP and PI for Tagliamento, Dora Baltea, Rhine and Inn-Salzach-Traun glacier subdomains.

We prefer not to share the monthly standard deviation of daily mean temperature as they are not directly connected to the present work.

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?

A: We slightly reformulated the text specifying the location of the caves (one in western and one in eastern Alps) and add a reference for Luetscher et al. (2015) in the discussion about the atmospheric circulation. The seasonality and moist air masses path proposed da Luetscher et al. (2015) fit our data. Concerning the conclusion of Spötl et al (2021), they suggest more autumn precipitation (mainly solid) that partially insulate the ground from wamring during summer. We expect frequent snowfall events also during summer at the Obir cave (>2000m), but we cannot exclude that in summer the snow on the ground melted while in autumn remained.

- l. 73 "simulated temperature and precipitation (Žebre 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.

A: We added in the introduction: “More precisely, the ELA is defined as the spatially averaged altitude of the set of points on the surface of the glacier where the ice mass balance is zero at a given time (Cogley et al. 2011). When the ELA is inferred at a regional scale without considering the effects of the morphology of the surface (i.e. shading, avalanching, snow drifting, glacier geometry or debris-cover) and it is averaged over at least some decades, it is called environmental ELA (envELA) which represents the theoretical altitude where a glacier can form and be sustained in a region (Anderson et al., 2018). Therefore, changes in ELA are especially powerful indicators of climate-glacier interactions. Here, we estimate the envELA of Alpine glaciers at 21 ka BP and pre-industrial (PI) times following the methodology developed by Žebre et al. (2020). We calculate the envELA using a simple parametric equation based on the theory of mass and energy conservation, which relates simulated summer temperature and annual precipitation (Ohmura and Boettcher, 2018) disregarding the local topographic effects acting on glaciers. An advantage of this method is that it does not require elaborate input datasets as in more sophisticated approaches which include the glacier dynamics driven by mass balance processes (e.g., Huss and Hock 2016; Zekollari et al., 2020)."

- l. 74 You refer alternatively to Žebre et al. (2020), Žebre (2020) and Žebre et al. (2021) but only the latter is included in the reference list.

A: The right one is Žebre et al. (2020)

Methods

- l. 82 "two 20 years time slices": is 20 years also the duration of the regional simulations?

A: yes

- l. 83 "LGM standard and PI": please define "LGM standard and PI", and spell out "PI".

A: Ok, defined in the abstract and introduction. LGM standard = 21 ka BP

- 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.

A: Same answer for general comment “Surface topography”

- 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?

A: Added in the paragraph 2.1: “The 20-year-long RCM data are then post-processed by removing an initial 1-year spin-up period and the four grid point wide lateral buffer zone, an area on the edge of the domain where the MPI-ESM-P forcing conditions are assimilated by the RegCM4 (e.g. Giorgi 2019). The resulting 19-year-long simulations over the interior of the domain are then used for the analysis. ”

- l. 118-119 "we assume that glaciers are at a steady-state": this is an important simplification (see general comment).

A: Answered in the general comment “Steady state”

- 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.

A: In the methods (2.5 Environmental Equilibrium Line Altitude): “This equation relates glacier and climate conditions; it was first introduced by Ahlmann (1924) in the form of a precipitation/temperature diagram (P/T diagram) and then recently updated by Ohmura and Boettcher (2018) using temperature, precipitation and solar radiation data from 104 glaciers worldwide. The P/T curve can be approximated by a quadratic function and is based on the principles of mass and energy conservation”

In the introduction it was explained why we use it: “An advantage of this method is that it does not require elaborate input datasets as in more sophisticated approaches which include the glacier dynamics driven by mass balance processes (e.g., Huss and Hock 2016; Zekollari et al., 2020).”

- l. 130 "validated for the Alpine region by Žebre (2020)": please add a few words here to understand which time period and which type of data have been used for validation.

A: Ok. “This method has already been validated for the Alpine region by Žebre et al. (2020) using two different ELA datasets: i) the Fluctuation of Glaciers (FoG) database of the World Glacier Monitoring Service (WGMS), from which geographically and climatologically distributed end-of-mass-balance-year ELA values over the Alps were selected for the period 1948 – 2017; and ii) the annual highest end-of-summer Snow Line Altitude (SLA) derived from Landsat data for the western Alps for the period 2006-2019, which was analysed using a semi-automated remote sensing method (Racoviteanu et al., 2019).“

- 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?

A: (Referred to the 2 previous comments) We delated the paragraph referred to the CWT and modified the results consequently.

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.

A: ok

- 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.

A: "greater" alpine region” is a term already used by Auer (2007) to define an area in the Alpine domain. Here we added also the domain coordinates for the domain used for the simulations and for the domain used for bias correction

- 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.

A: We briefly summarise the GCM output, which was already detailed by other studies e.g. Ludwig et al. (2016)

- 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.

A: Ok, we split in 2 sections as it was not possible to separate temperature from pr and winds.

- 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.

A: We added some details, but the first paragraph is mainly based on the anomaly (LGM-PI) and not only on the LGM and the second already includes comparisons with the PI, which was anyway made more evident.

- 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.

A: We added the requested panels for the PI

- Figs. 1-3 Are these 19-year averages as in Fig. 4? Please clarify in figure captions. ok
- l. 161 "All these findings indicate a strong influence of the Siberian high": maybe this belongs to the discussion

A: ok, removed from here. In the discussion there is already a statement referring to the anticyclonic circulation generated by the high-pressure over the Scandinavian ice sheet.

- l. 188 "We used daily data from 19 simulated years": I think this information should also appear in the caption of Fig. 4.

A: ok

- l. 208 "The envELA calculations were performed following the method proposed by Žebre et al. (2021) (Eqs. 3, 4, see methods)." The reference year is different from the methods parts.

A: The right year is 2020.

- l. 216-221 "By comparing the envELA with the model topography" This paragraph belongs to the discussion.

A: We split the paragraph in two: the first sentence better explains our results, while the second was moved 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".

A: This paragraph was reformulated as: "The RegCM4 cannot capture the multitude of small glaciers present at the PI over the whole Alpine region but can identify areas where the envELA is lower than the model topography, which occur mostly in the western Alps (Fig. S6). Conversely, at 21 ka BP the larger glacier systems are better captured by the model (Fig. S5).".

We also added an analysis in which the envELA is related to the topography (Figs. S5 and S6), highlighting that when the envELA is lower than the topography we can assume that the glacier produces the correct T/P conditions leading to the formation and maintnance of the glacier.

- 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?

A: (Referred to the 2 previous comments) We deleted these assumptions as they would require a much longer analysis which is beyond the scope of this paper. JS is right in his observation. In this paper we considered the monthly mean temperature, but single days of above 0 °C were of course possible.

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.

A: Ok, split into:

- EnvELA - comparison with other studies
- Limitations and consideration about the experimental set-up
- Links between glacier behaviour and topography
- EnvELA and geological reconstructions
- Atmospheric circulation

- 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.

A: ok

- l. 253 "our envELA shows a drop consistent with the geological reconstructions (Ehlers et al., 2011)." please see general comment.

A: We added this sentence: ”Despite the different time responses of envELA and glacier extention to changes in climate, since the envELA is directly related to temperature and precipitation while the glacier extention has a lag due to ice dynamics, according to Žebre et al. (2020) the envELA variations can be associated with variations of the front position and the effective ELA of glaciers (i.e. the ELA calculated from geodetic or direct glaciological mass balance measurements). Also, the envELA calculations allow a more detailed discussion of local differences in the geological reconstructions over the Alpine region.”

- 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).

A: Ok, changed into mass balance processes

- l. 266 "Our LGM simulation refers to 21 ka BP": this needs to appear earlier.

A: Ok, now it appears since the introduction

- 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.

A: Consideration about the topography were made (ad are now extended) and included in a new dedicated section (4.3)

- 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.

A: Ok, Fig. S4

- 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.

A: It is not really clear from Fig. 1 (that now includes also the PI), where it is possible to see only a slight rotation of the main winds and a change in their intensity, in a way that anyway matches the southward shift of the north Atlantic jet. We think it is more evident from the windroses (fig.4 and S2) especially for rhine basin.

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.

A: We reformulated: "Our reconstruction allows us to better understand the different behaviours of the Alpine glaciers in light of the morphology of their accumulation basins as well as some of the shortcomings between previous LGM glacier reconstructions based on ice-flow dynamics and geomorphological evidence.

Technical corrections

- Many abbreviations are used, some of which are not spelled out. Please make sure that every abbreviation in the text is defined.

A: ok

- 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.

A: “ice stream network” was substituted by “interconnected valley glaciers”

- 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.

A. substituted by “ice sheet complex”

- l. 67 "Therefore, here" I suggest to break the paragraph here, (and maybe remove "therefore"), before the content of this study are announced.

A: ok

- l. 75 "LGM glacier mass balance": change to "LGM ELA".

A: ok

- l. 123 Eqn. 3. Units for the constants are missing.

A: Ohmura and Boettcher (2018)

- Figs. 1-3 is summer / winter (Fig. 1) the same as JJA / DJF (Fig. 2)?

A: Yes, it is JJA in both case and the new version of Fig. 1 is now labelled with JJA

- Fig. 3: there is probably a mistake in precipitation units or values, even Bergen is not that rainy!

A: We changed the units in mm/yr

- l. 165 "pver" -> "over"

A: ok

- l. 187 "four Alpine piedmont glaciers" -> "four subdomains corresponding to LGM Alpine piedmont glaciers"

A: ok

- l. 192 "more events" -> "more precipitation events"

A: ok

- l. 311 "alpine" -> "Alpine"

A: ok

- l. 379 "coditions" -> "conditions"

A: ok

- l. 383 "agreemtn" -> "agreement"

A: ok