Climate of the Past Discussions

Clim. Past Discuss., author comment AC2
https://doi.org/10.5194/cp-2022-43-AC2, 2022

Reply on RC1

Costanza Del Gobbo et al.

Author 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-AC2, 2022

Our replies to comments are in bold type:

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 climatic mass balance is zero at a given time (Cogley et al. 2011). When the ELA is inferred at a regional scale without considering the effect of topography (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) and 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 thus estimate the envELA of Alpine glaciers for 21 ka BP and the pre-industrial time (PI) 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), thereby 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): "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 grounded 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_JJA) 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: We need to compute T_JJA via eq.3 to find the delta T from the RegCM temperature, which is then used to calculate the delta H by means of the env lapse rate. This is then subtracted by the DEM in order to obtain the envELA for every grid-cell.

- 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 sea level by 120 m (Peltier and Fairbanks, 2006) and changed the land sea-mask in order to take into account 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 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 one. The three resulting envELA datasets are then averaged. Because the observational and simulated datasets do not use the same horizontal grid, we remapped RegCM4 and LAPrec data onto the HISTALP grid of 5 arcmin resolution"

- 216 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. S4 and S5) 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. 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 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 commentsMinor comments

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

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

- 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 glacier 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"

- **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. S2) 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