Dear Editor,

On behalf of the co-authors, I am writing to submit a revised version of the paper entitled *“Atmosphere-cryosphere interactions during the last phase of the LGM (21 ka BP) in the European Alps”* (research article CP-2022-43) to the journal Climate of the Past, pending minor revisions.

Following your suggestions, our responses to the reviewer's comments were partially adjusted, especially in those parts that could sound too defensive.

Nevertheless, after changing some replies (in this regard we add for your convenience a clean version of the point-by-point reply and a track changes one) and further modifying some texts as you will see, we also modified two figures (figs. 2 and 7) according to the last referee’s comment. The manuscript has been checked for typos, as you requested. The only point we still did not fully address concerns the chosen lapse rate for LGM and PI. Our choice is supported by the literature (Žebre et al., 2021) as we explain in the response to the reviewer's comments.

We look forward to hearing from you,
sincerely,

Costanza Del Gobbo

For the sake of clarity, we provide a clean version of the point-by-point response to the referee's comments together with a track changes one.

- **Julien Seguinot - referee #1**
    - There remain several typos in the text especially on author names (Becker, Imhof, Velasquez) and other inconsistencies such as using "et al." for a single author reference. I think it is important to fix these inconsistencies before publication but leave this for the typesetting stage.

A: OK

- Eqn. 3 units are still missing. I did not understand the authors' response to my comment with a single reference to "Ohmura and Boettcher (2018)." Eqn. 3 links temperature and precipitation via numerical constants, but without knowing the units or the constants, or if temperatures are in °C or K and precipitation in kg or mm, it is impossible to interpret the equation.

A: We added at l 161: "P_{corr19} is expressed in millimetres and T_{ELA} in degrees Celsius. The standard error of the method is 648 mm."

- I find fig. S5 very useful, perhaps even more useful that the envELA map included in the paper (fig. 5). By showing the difference between the DEM and envELA (i.e. right part in Eqn. 4) it becomes much more clear which parts of the mountain range are prone to ice build-up. I would suggest to include it in the main text.

A: OK, it is the new fig. 6.b (all other figure numbers were adjusted accordingly)

- I actually preferred the previous (shorter) title without "the last phase of the LGM". The intro and methods now make it clear which period(s) you focus on (this was one critic in my previous review), so I don't think the longer title is needed.

A: We would prefer to maintain the title: 'Atmosphere-cryosphere interactions during the last phase of the LGM (21 ka BP) in the European Alps', which provides a more explicit reference to the time period studied, as also suggested by another referee.

Anonymous referee #3

General

The study is well structure and well written. The overall topic of the study is interesting and certainly valuable enough to be published, although it seems to be sometimes that the authors do not take enough caution on what we know so far and what is newly found be the authors. I would say that the authors mainly confirm existing knowledge also form the other model studies. Still, a confirmations of other modelling result is important so This is why I support this study. Given some of my comments below I recommend to publish this manuscript after major revisions.

A: Through the text, we added several citations and tried to be clearer about what was newly found by us and what was already known. It is true that some aspects related to our model output confirm other model studies. This was used to validate our simulations before reconstructing the envELA. Indeed, the main outcome of this work is the envELA reconstruction. The manuscript represents the first reconstruction of the envELA for the LGM over the whole Alpine range. The most notable outcome relates to existing geomorphological evidence, addressing several issues existing in previous ELAs reconstruction.

Furthermore, to calculate the envELA we use LGM and PI simulations run with the RegCM4 model, which has never been used in a paleoclimate study in the Alpine region before. Thus, we provide a new dataset that can be employed in future studies.

1. In particular, the discussion needs to substantially improved.

A: We now expanded section 4.2 (limitations of the method) and 4.5 (Atmospheric circulation), as suggested by the reviewer in the next comments.

2. Also, a more detailed analysis of the seasonality is needed, to compare with existing literature. The effect of the bias correction is not well treated and a comparison between simulation and proxy records is missing.

A: We expanded the results and discussion sections related to a comparison with proxy records and the seasonality of the atmospheric circulation. Winter and summer subplots for precipitation and precipitation anomaly were added as well.

However, since the main goal of this paper is the envELA reconstruction, which is based on yearly precipitation and summer temperature, we tried to keep the new analysis concise, as an extremely detailed seasonal analysis of the climate variables over the whole domain is beyond our scope.

Comments

3. **L12**: Please add a comma after "Here"

A: OK

4. **L34**: superscript "2" for the unit of area.

A: OK

5. **L45**: There is a new estimate for temperature change between LGM and PI: Annan, J. D., Hargreaves, J. C., and Mauritsen, T.: A new global surface temperature reconstruction for the Last Glacial Maximum, Climate of the Past, 18, 1883–1896, hlps://doi.org/10.5194/cp-18-1883-2022, 2022.

A: OK

6. **L50**: Please add the following review paper here: Raible, C. C., J. G. Pinto, P. Ludwig and M. Messmer, 2020: A review of past changes in extratropical cyclones in the northern hemisphere and what can be learned for the future, WIREs Climate Change, 12, e680. hlps://doi.org/10.1002/wcc.680

A: OK

7. **L55**: I think the references are misplaced here as they reconstruct the alpine ice cap during LGM – all the dynamical interpretation are hypotheses in these papers so maybe cite Raible et al. 2020 or other modelling-based papers, e.g. Ludwig et al. 2016, 2017

A: This is true. We added Ludwig et al. (2016). However, also Raible et al. (2021) cited Luetscher et al. (2015) and Florineth and Schlüchter (2000) when talked about Alpine ice build-up.

8. **L71**: I think, the authors need to include a paragraph on regional modelling for LGM times, as the presented study is not the first of its kind. Important publications are Ludwig et al 2016,2017, Velsaquez et al 2020, 2021, 2022, Pinto and Ludwig 2020 mentioned later in the manuscript.

A: As suggested by the reviewer, this paragraph was added: "In recent years, the number of studies using RCMs for palaeoclimatic applications has notably increased, providing much information about the LGM circulation in the North Atlantic and Europe. For example, Ludwig and Pinto (2020) explored the extratropical cyclones in the North Atlantic region; Shaffernicth et al. (2020) and Ludwig et al. (2021) analysed high-resolution climate simulations to study dust cycles and loess deposition; Imhof (2021) forced a hybrid ice sheet model with high-resolution (2 km) climate data to model the LGM Alpine ice fields; and Ludwig et al. (2017) and Velasquez et al. (2021, 2022) studied the role of sea surface temperatures, vegetation and ice-sheet topography in the Alpine climate during glacial times (LGM and MIS4)."

9. **L72**: Please add a comma after "Here"

A: OK

10. **L81**: Please add Kuhlemann et al. 2008 here.

A: OK

11. **Section 2.2**: Please define the domain in 50 km resolution and maybe show it in a figure together with the 12 km resolution.

A: We added the extension of the 50 km resolution domain in the main text ("The lower-resolution RegCM4 simulations (50 km) extend from 3.8 to 23.0 °E, and 37.5 and 51.0 °N...") and a figure (Fig. S1) in the supplementary materials.

12. **L130**: I do not understand why the authors only include the horizontal extent of the ice sheet and not the height. In Seguinot et al. 2018 they could have made use of a 3 dim estimate of the alpine ice cap.

A: We added explanations for this choice after the first round of review:

- 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 (2021) and Velasquez et al. (2022) highlighted the importance of including glaciers' topography into global and regional palaeoclimate models."
- 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 approach might introduce some uncertainty in the envELA estimations."

In this regard, to further clarify this aspect, we added an additional explanation in the paragraph 4.2 after the [*], as follow: "This is in contrast with the approach followed by Merz et al. (2015), Imhof (2021) and Velasquez et al. (2022). However, differently from us, these studies are based on climate data at a much higher resolution (2 km for Imhof, 2021 and Velasquez et al., 2022) or focused on regions with a very different topography compared to the Alps (Laurentide Ice Sheet and North Atlantic for Merz et al., 2015), where, at the LGM, the ice build-up generated a 4000 m high orographic barrier over a previously ice-free region. Conversely, at the LGM the Alps were characterized by ice domes and valley glaciers (Kelly et al., 2004; Ivy-Ochs et al., 2022) generally narrower than our model resolution (12 km) and they did not strongly modify the main alpine range profile."

13. **L134**: Given the importance of the vegetation changes it would be good to see how the constructed vegetation cover looks like.

A: Here, a figure representing the vegetation and two tables to clarify how the bioma are structured. We added a reference (Del Gobbo, 2021) where one can find these figure and tables and some explanations, based on extensive existing literature.

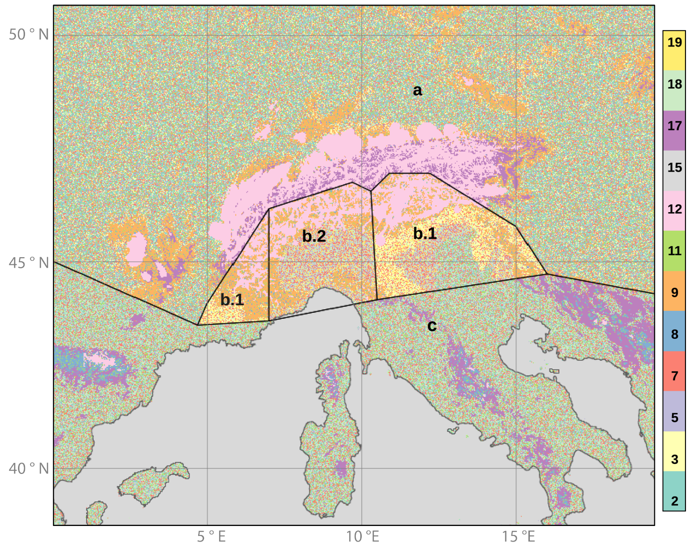

Figure R1: Reconstructed vegetation map. The black lines identify three sub-regions: (a) northern Alpine, (b.1) southwestern and eastern Alps, (b.2) West Garda Sector, and (c) Pyrenees, Apennines and Balkans. Each region is further divided into altitudinal bands chosen specifically for each area (Tab. 1). Every plant type is defined according to its corresponding BATS code (Tab. 2; Wilson et al., 1987), as shown in the colour bar on the right. Glaciers are in pink. The percentage of every plant type for each sub-region and altitudinal band is shown in tables 1 and 2.

Regions		**Bioma**	**Altitudinal Bands**
Northern Alps		Boreal Steppa	0 to 700 m
		Forest - Tundra	700 to 800 m
		Tundra	800 to 1200 m
		Desert	> 1200 m
Southern Alps	Western and Eastern Sector	Steppa	0 to 110 m
		Steppa - Forest	110 to 130 m
		Boreal Forest	130 to 700 m
		Forest - Tundra	700 to 900 m
		Tundra	> 900 m
	West Garda Sector	Steppa	0 to 110 m
		Steppa - Forest	110 to 700 m
		Forest - Tundra	700 to 900 m
		Tundra	> 900 m
Mediterranean		Steppa	0 to 900 m
		Tudra	900 to 1500 m
		Desert	> 1500 m
North Africa		Steppa - Forest	0 to 300 m and 1200 to 1500 m
		Temperate Forest	300 to 120 m
		Steppa	> 1500 m
Desert		Steppa	1000 to 1500 m
		Desert	0 to 1000 m and > 1500 m

Table R1: Subdivision of every region into altitudinal bands and the corresponding bioma

Bioma	Plant Type	%	BATS	CLM
Steppa	Short Grass	20	2	14
	Deciduous Broadleaf Tree	10	5	8
	Semi-Desert	15	11	1, 14
	Deciduous Shrub	35	17	11
	Tall Grass	20	7	14
Boreal Steppa	Short Grass	35	2	13
	Tall Grass	15	7	13
	Deciduous Broadleaf Tree	10	5	9
	Semi-Desert	10	11	1, 13
	Evergreen Needleleaf Tree	10	3	3
	Tundra	10	9	12, 13
	Deciduous Shrub	10	17	12
Steppa-Forest	Deciduous Broadleaf Tree	20	5	8, 9
	Tall Grass	25	7	13, 14
	Deciduous Shrub	25	17	11, 12
	Mix Woodland	15	18	2, 3, 4, 8, 9, 10, 11, 12
	Forest/Field	15	19	2, 3, 4, 8, 9, 10, 11, 12, 13, 14
Temp. Forest	Deciduous Broadleaf Tree	20	5	8
	Tall Grass	15	7	14
	Deciduous Shrub	10	17	11
	Mix Woodland	20	18	2, 4, 8, 10, 11
	Forest/Field	10	19	2, 4, 8, 10, 11, 14
	Evergreen Neadleleaf Tree	25	3	2
Boreal Forest	Evergreen Needleleaf Tree	40	3	3, 4
	Tall Grass	20	7	13
	Deciduous Shrub	10	17	12
	Mix Woodland	20	18	3, 9, 10, 12
	Forest/Field	10	19	3, 9, 10, 12, 13
Forest-Tundra	Evergreen Needleleaf Tree	25	3	3, 4
	Tundra	50	9	12, 13
	Deciduous Shrub	10	17	12
	Evergreen Shrub	10	9	12
	Deciduous Broadleaf Tree	5	5	9
Tundra	Desert	10	8	1
	Tundra	80	9	12, 13
	Semi-Desert	10	11	1, 13
Desert	Desert	80	8	1
	Semi-Desert	20	11	1, 13
Glaciers	Glaciers	100	12	1
Ocean	Ocean	100	15	1

Table R2: Percentages of plant types per every bioma with the corresponding BATS (Wilson et al., 1987) and CLM codes (Oleson et al., 2013).

14. **Section 2.4**
    a. Why is a bias correction needed. The authors destroy a bit the physical connection between precipitation and temperature. Would the results change if the not bias corrected is used to estimate ELA.

A:

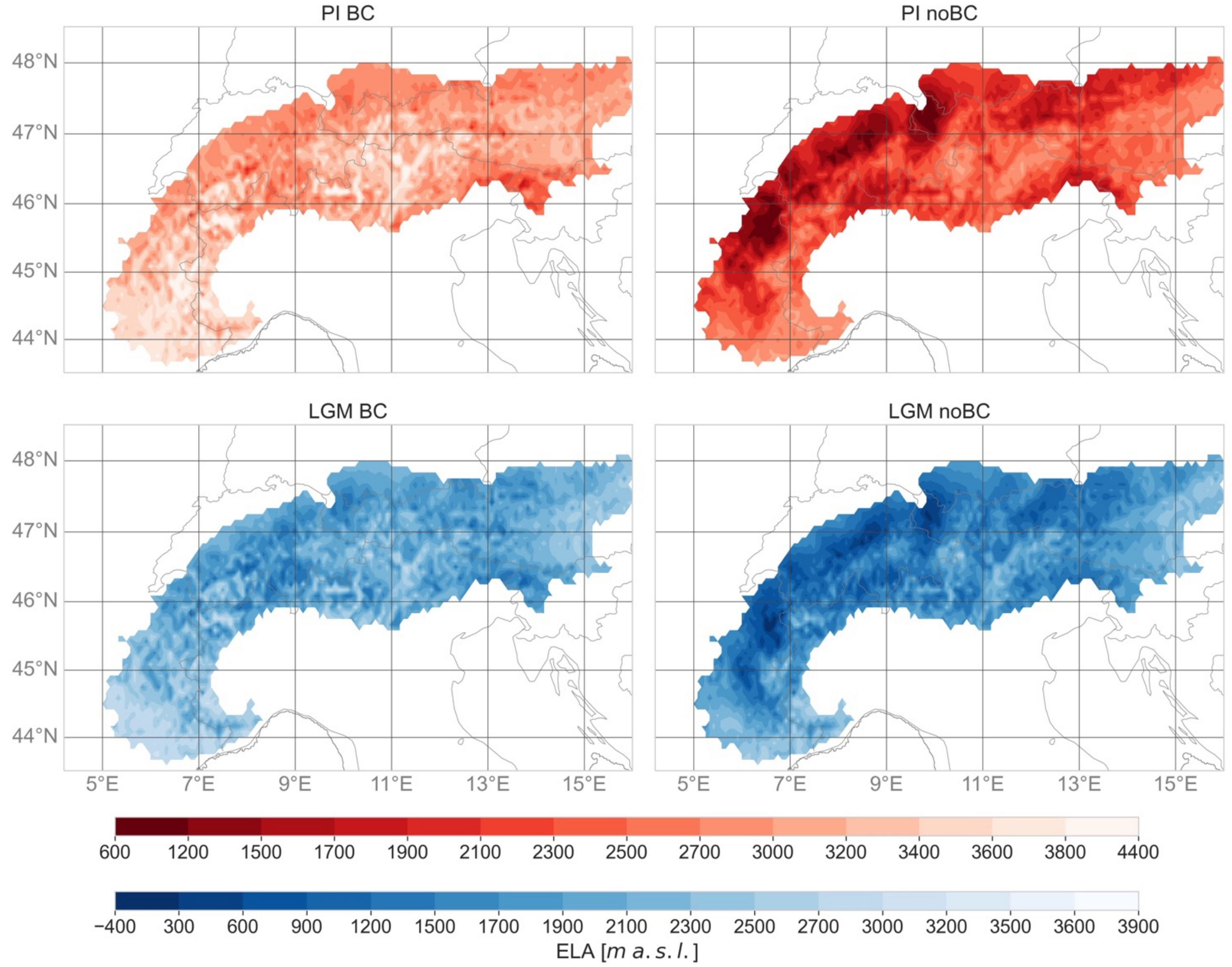

Figure R2: envELA calculated from PI (first row) and LGM (second row) bias-corrected (BC) and non-bias-corrected (noBC) RegCM4.

Yes, it changes (Fig. R2). The average difference of the envELA calculated with bias and non-bias-corrected data over the Alps, ranges between 450 and 900 m on average. Western Alps show particularly low envELA values, when no bias correction is applied (darker colours in fig. R2). After the analysis of pre-industrial simulation (PI) vs historical observations (LaPrec and HISTALP 1871-1900) and despite the expected tuning performed before running the simulations, it was evident that the model had a wet bias in the precipitation, which is particularly strong on the western Alps (fig. S3), and a cold bias in summer temperature over all the domain and on the Alps all year round (fig. S2). In general, biases in temperature and precipitation are considered normal in climate modelling also at the highest resolution of convection-permitting.

We added two paragraphs:

- in the introduction: “However, regardless of the fine scale of RCMs, the simulated precipitation patterns can still show substantial biases (Ban et al., 2014; Velasquez et al., 2020; Gómez-Navarro et al., 2018; Casanueva et al., 2016; Rajczak and Schär, 2017) which may affect hydrological and glacier models being forced by RCM data (e.g., Imhof, 2021; García-Valdecasas Ojeda et al., 2022). Thus, a bias correction can be required in order to correct RCM errors (Velasquez et al., 2020)."

- In the methods: "Despite the fine resolution used and the model customization, biases can still affect RCM output data due to initial and boundary conditions from the driving GCM (the MPI-ESM-P is characterized by a northward shift of the upper-level North-Atlantic jet stream; Ludwig et al., 2017) as well as the parameterization of processes occurring at finer scales than the simulations' resolution (Velasquez et al, 2020). Since we need absolute temperature and precipitation values to reconstruct the envELA, we thus applied a first-order bias correction to our data, in order to account for model biases such as a cold bias in temperature over the Alpine range and a wet bias in precipitation over the western Alps (fig. S2 and S3)."

We stress that this work represents the first reconstruction of the envELA for the LGM over the whole Alpine range, and, according to geomorphological data, better resolves different regions where previous model studies showed several issues. However, for sure, future improvements can be carry out as different assumptions and simplification were made.

b. Also, it would be good to show the biases in temperature and precipitation.

A: Figures S2 and S3 were added, showing PI temperature and precipitation (yearly, DJF and JJA) for non-bias-corrected RegCM4 data, bias-corrected RegCM4 data, and the bias between PI non-bias-corrected RegCM4 data and observations.

c. I also would like to mention that the observations strongly underestimate precipitation in complex and high terrain (Frei et al. papers), so maybe the model is even more realistic in that variable using the not corrected values.
    i. Frei, C. and Schär, C.: A precipitation climatology of the Alps from high-resolution rain-gauge observations, Int. J. Climatol., 18, 873–900, hlps://doi.org/10.1002/(SICI)1097-0088(19980630)18:8<873::AIDJOC255>3.0.CO;2-9, 1998.
    ii. Frei, C., Christensen, J. H., Déqué, M., Jacob, D., Jones,R. G., and Vidale, P. L.: Daily precipitation statistics in regional climate models: Evaluation and intercomparison for the European Alps, J. Geophys. Res.-Atmos., 108, 4124, hlps://doi.org/10.1029/2002JD002287, 2003

A: OK, we mentioned this aspect and cited Frei and Schär (1998) in the discussion (section 4.2).

15. **L156**: Please change methodology to Method throughout the text as both words have a different meaning.

A: OK

16. **L168**: The authors assume a constant lapse rate but the lapse rate will change rather strongly between LGM and PI so I suggest to calculate the lapse rate from each model simulation (PI and LGM separately) and use this to estimate the envELA.

A: We calculated the summer lapse rate over the Alpine range for LGM and PI from our simulations which resulted in 0.7 °C/100m for the bias-corrected LGM and 0.56 °C/100m for the bias-corrected PI and observations. Compared to the literature PI/OBS lapse rate are too low by 0.09 °C/100m (Figure R3). Calculating the envELA with the different lapse rate, we obtain a difference of 45 m (283 m) for the LGM (PI), which fall in the range of error of the method.

Considering these elements, we prefer to use the value of 0.65 °C/100m. We also chose to be consistent with the first existing work on this topic (Žebre et al., 2021) that uses the same lapse rate to calculate the envELA till 2100, under different RCP scenarios (RCP2.6, RCP4.5, and particularly RCP8.5).

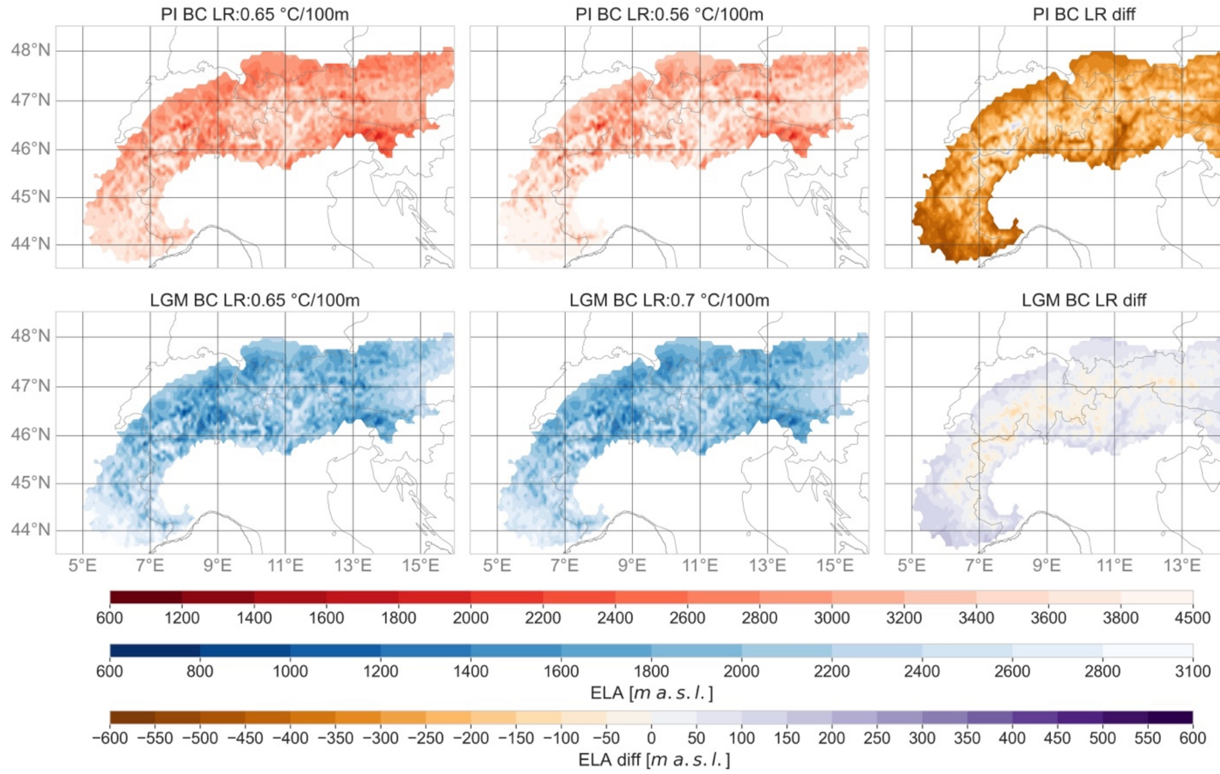

Figure R3: PI (first row) and LGM (second row) envELA calculated with different lapse rate and their difference.

17. **L188**: In Ludwig et al. 2017 the authors showed that the MPI ESM simulations has a rather strong biases in the North Atlantic so was this here corrected? At least this needs to be mentioned that there are also biases in the driving GCM.

A: We applied the bias-correction on the RegCM4 simulations and we added:

- in the methods (section 2.1): "*The MPI-ESM-P has already been successfully employed in the study of the LGM (e.g., Pinto and Ludwig, 2020; Stadelmaier et al. 2021), showing a northward shift of the upper-level North-Atlantic jet stream when compared with the multi-model mean of the CMIP5/PMIP3 and CMIP6/PMIP4 projects (Kageyama et al., 2021). This behaviour is possibly associated with a strong influence of the Scandinavian ice sheet in Central Europe. Overall, however, the behaviour of the MPI-ESM-P is in line with that of other models (Ludwig et al., 2016) and, given the agreement of this model with proxy records (permafrost and ground cracking extent; Stadelmaier et al. 2021) we can assume that the LGM large-scale circulation is represented in a reasonably accurate way by the MPI-ESM-P, thereby providing realistic forcing data for the RegCM4.*";
- and in the section 3.1 of the results: "...*although the LGM upper-level North-Atlantic jet stream is stronger over the northern parts of the North Atlantic compared to other models (Ludwig et al., 2016).*"

18. **L204**: Are DJF really the coldest months, not that insulation has changed.

A: Yes, they are. According to our data, at the LGM on the Alps the difference between February and March temperature is smaller than at the PI, but February was always colder than March.

19. **L216**: Compared to the driving GCM (9C the 6.6C temperature response is substantially weaker, why is that. I would have expected an even stronger response as orography is between resolved in the RCM than the GCM?

A: Because the 9 °C anomaly refers to the whole central Europe, thus to a broader region compared to the area where 6.6 °C were calculated, i.e., the domain of the RegCM simulations. The GCM data is influenced by the proximity of the Scandinavian Ice Sheet, which causes lower average temperature. However, as hypothesized by the reviewer, considering only the Alps, the temperature anomaly is stronger in the RegCM than in the GCM.

20. **L235-239**:

a. The dynamics might have changed if the authors would have implemented an ice cap so at least a more cautious discussion is needed.

A: We replied to this comment above, line 130.

b. Also, the level of detail (going down the level of single glaciers) is too superficial given the resolution of 12 km.

A: The analysis of ll235-239 is obtained not studying a single cell of 12 km for each glacier but studying a larger region surrounding the glacier basin (shown in new fig. 5).

c. Please check the later comment throughout the manuscript.

Later in the text (section 4.3) we compare the envELA with effELA from other studies, but we also stress on the difference between these two types of ELAs. The envELA has the characteristic of being regional and climatic and for this reason was provided as range of values rounded every 50 meters. A comprehensive discussion about this aspect is given in Žebre et al. (2021), sections 4.1 (environmental vs effective ELA), 4.2 (model uncertainties), 4.3 (link between envELA and historical observations of glaciers fluctuations). In particular, in that paper the authors reported that *"... the envELA is ~ 75−150 m higher than the regional effELA when averaged over a longer climate period, e.g. 15−30 years. The difference between envELA and wgmsELA might also be related to the fact that the glaciers selected for measuring annual glacier mass balance by the WGMS are those with easier access and thus tend to be located on lower altitudes, consequently having on average lower ELAs. While the envELA is consistently higher than effELA, the time series pattern is in general well reproduced (Fig. 9)...".* For convenience we copy and paste figure 9 and 10 of Žebre et al. (2021) with captions.

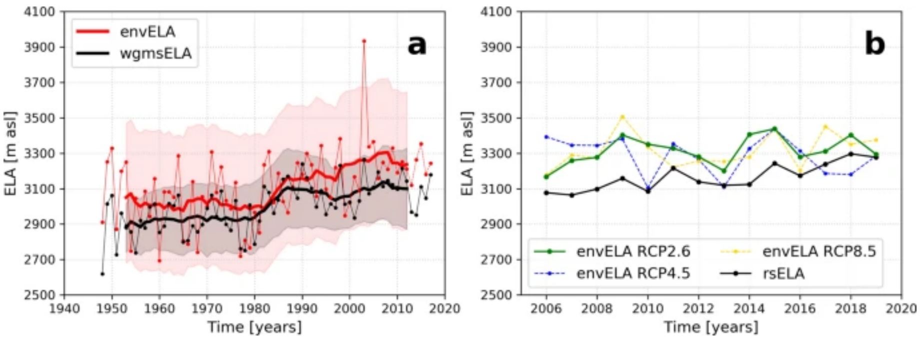

Figure R4: **a** Comparison between the envELA averaged over the grid cells as defined in Fig. 1 and average regional wgmsELA for 62 glaciers for the period 1948−2017. The last 12 years (2006−2017) of the envELA (dashed line) represent average of all three RCPs envELAs. Thick lines correspond to 11-year centred running mean, thin lines represent yearly variations, and transparent bands correspond to the standard error of Eq. 3 (i.e. 648 mm) for the envELA and sample standard deviation for wgmsELA. (b) Comparison between the rsELA derived from Landsat images and envELA derived from climate projections under three different scenarios (RCP2.6, RCP4.5 and RCP8.5) for the period 2006−2019 over the rsELA extent as defined in Fig. 1.

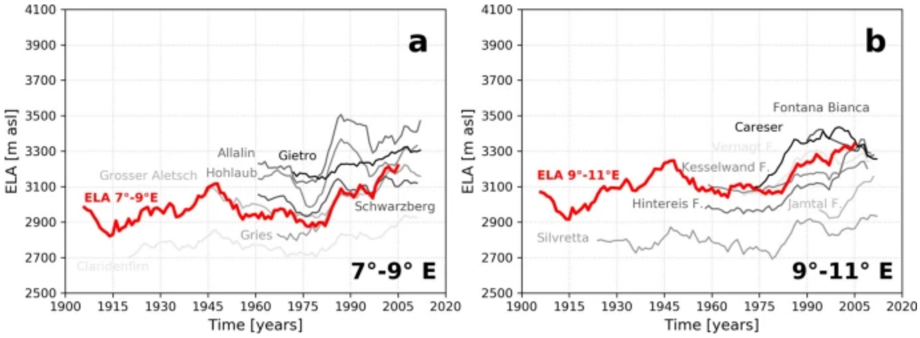

Figure R5: The wgmsELAs of 14 glaciers located in the sectors **a** between 7° and 9°E longitude and **b** 9° and 11°E longitude. Lighter lines equate to northern located glaciers and darker lines to southern located glaciers. In red is the envELA averaged over that same sector. All ELAs are presented as 11-year centred running means.

21. **Fig. 1**: Please show only precipitation and wind arrows. The other lines are making the plots too busy. Also note that temperature and precipitation will be shown also in Fig. 2 and 3.

A: In order to make the figure tidier, as suggested by the reviewer, we split it in two parts. Now, in the first row there are winds and precipitation, in the second one geopotential height and temperatures. This figure is meant to summarize the model outputs (without bias correction), giving a global idea of the circulation. We believe that it is important to keep also temperatures in this figure because in figure 2 (old figure 1) temperature and precipitation are not bias-corrected, differently from figures 3 and 4 (old figures 2 and 3).

22. **Fig. 3**: Please add DJF and JJA and discuss the seasonality of the signal in the manuscript. I think in one of Velasquez papers these authors see that in summer precipitation is reduced and in winter increased, which contradicts these results.

A: We added winter and summer PR to the figure. In the text we already mentioned winter and summer precipitation in section 3.2.2., but we added sone further analysis.

- Results: *"...with the most pronounced cooling and drying occurring in summer (-7.3 °C of cooling and -38.1 % of drying) [...] Summer anomalies are always more pronounced than winter anomalies in both regions (Fig. 4)."*
- and discussion as: *"This contradicts the findings of Velasquez et al. (2021; 2022) who, analysing high-resolution LGM climate simulations over the Alps, obtained significantly heavier precipitation rates during winter than during summer, with maxima in the Western Alps. Winter precipitation anomalies in both Velasquez's et al. (2021; 2022) and our study present negative values north of the Alps and positive values in the south. Conversely, differently from Velasquez et al. (2021; 2022), during summer we find a positive precipitation anomaly in the southern part of the domain (Fig. 4). This result suggests increased convection and cyclonic circulation in the northern Tyrrhenian region at 21 ka BP. The discrepancies with Velasquez et al. (2022) are possibly caused by differences in the driving GCM, the way convection is represented in the RCMs, and the bias correction applied in this study."*

23. **F.2 and Fig3**: I am interested in the response between LGM and PI when no bias correction is introduced in particular for Fig. 3.

A: The difference between bias-corrected and non-bias-corrected anomalies for temperature is 0 (excluding the sea) (fig. R6), as the same bias correction was applied to PI and LGM. For precipitation it varies with space, as the correction is multiplied to the model data (fig. R7).

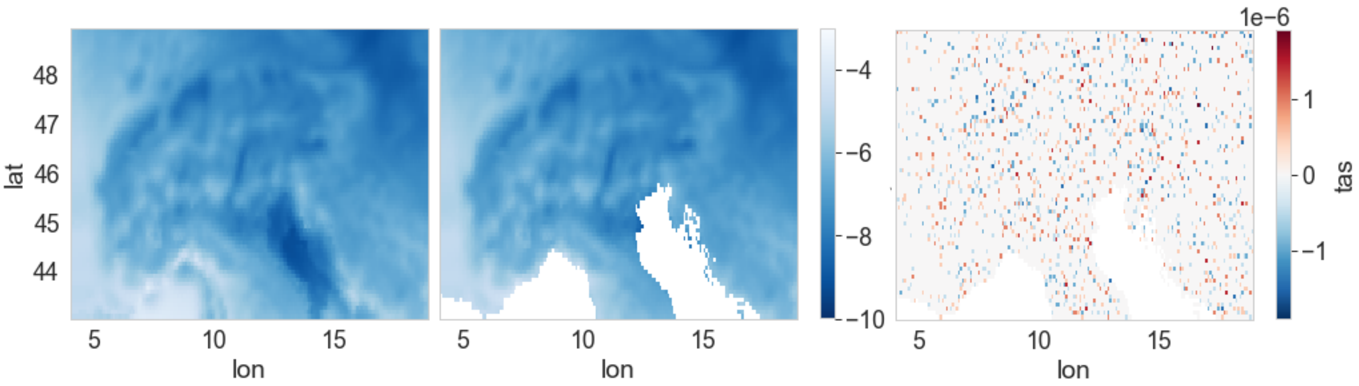

Figure R6: LGM-PI temperature anomaly (in °C) without bias-correction (left) and with bias-corrected (centre). On the right the difference between the other two boxes.

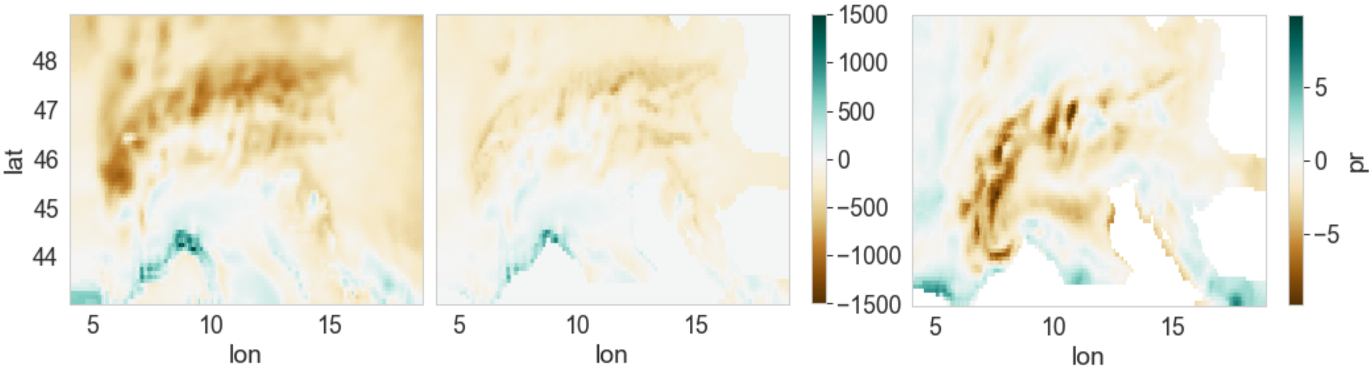

Figure R7: LGM-PI precipitation anomaly (in mm) without bias-corrected (left) and with bias-corrected (centre). On the right the difference between the other two boxes.

24. **L267**: Please remove "can" here

A: OK

25. **Fig.4 and discussion of Fig. in the MS**: To me it is not clear whether you show wind direction and precipitation or wind direction under the condition that there is precipitation. The second one would make much more sense.

A: The reviewer is right; it is the second one. Fig. 5 and S4 labels have been updated: "21 ka BP (PI) seasonal wind origins associated to each of the 19 simulated years precipitation event. This has been done for Rhine, Inn-Salzach-Traun (IST), Tagliamento and Dora Baltea glacier subdomains. Windroses show the main wind directions under the condition that precipitation events occur. Colours represent precipitation intensity in millimetres and colour band width is the frequency of a given precipitation intensity per wind direction. The shadow in the map is the glacier extension (Ehlers et al., 2011), the colour lines as well as the full colour in the boxes represent the topography (yellow for higher elevation and green for the lowers) and the black line is the present-day political boundary."

26. **Fig.5**: how would this figure look like if no bias correction is applied.

A: Please, see answer to comment about Section 2.4 and Fig. R2.

27. **L291-295**:
    a. I think the authors need to show a model-proxy comparison. Just saying that it is good is not sufficient.

A: Thanks, we realised this part was missing. We added this table in the supplementary (Tab. S1), that shows 21 ka BP - PI anomalies for our simulations, Wu et al. (2007), and Pini et al. (2022). And the following text: "*In the bias-corrected domain, few proxies are available for evaluating the simulated climate (Wu et al., 2007; Pini et al., 2022). The RegCM4 data show cooler and drier conditions for 21 ka BP, in agreement with temperature and precipitation pollen-based* *reconstructions for the coldest and warmest months of the LGM (Wu et al., 2007). In line with other model studies, absolute values of simulated temperature and temperature anomalies underestimate proxy values (Pini et al., 2022). This is possibly caused by model shortcomings or by the higher proxy sensitivity to climate extremes than to climatological mean states (Kageyama et al., 2006; Velasquez et al, 2021).”*

		ΔT_{JAN}		ΔT_{JUL}		ΔP_{JAN}		ΔP_{JUL}	
LAT	**LON**	**Proxy**	**RegCM**	**Proxy**	**RegCM**	**Proxy**	**RegCM**	**Proxy**	**RegCM**
[†]47.73	6.5	-17.6	-9.5	-11.8	-5.1*	-17.0	-13.0	-23.7	-18.4
[†]45.67	4.89	-11.4	-7.7	-7.6	-5.4	-19.4	-1.5	5.3	5.6
[‡]45.27	11.74	-23.0	-10.2*	-9.6	-6.5*	/	/	/	/

Table R3: *21 ka BP-PI temperature and precipitation anomaly of January and July. The values are averaged over the 19 years of the RegCM4 simulations considering the nearest model grid point to the pollen site. Pollen-based reconstructions are from: Wu et al. (2007)[†] that provide a central value and a 95% confidence interval corresponding ±60 mm month^{-1} for precipitation anomaly, ±10–20 °C for January temperature anomaly and ±3–5 °C for July temperature anomaly; and Pini et al. (2022)[‡] whose error is 4.4 °C for ΔT_{JAN} and 2.0 °C for ΔT_{JUL}. * The value falls out of 95% confidence interval or the method error.*

b. Also show how the biases correction affects the results.

A: Please, see answer to comment about section 2.4 and Fig. R2.

28. **L315**: “In fact”

A: OK

29. **Section 4.2**: I suggest to include also a discussion on the effect of the bias correction and its limitation. The basic problem is that any bias method assumes stationarity, so that biases are independent from the state estimated. This might be OK for climate states not so different to the reference state but during the LGM the climate is very different so it might be problematic to apply such corrections.

A: Thanks for the observation. This was now added in section 4.2: “In order to at least partially address these errors, a bias correction was applied to the RegCM4 output. However, further uncertainties can be introduced by calculating the correction function from limited observations, which may suffer from the rain gauge undercatch and the misrepresentation of high-altitude regions (Frei and Schär, 1998). In addition, the application of the same bias correction method to very different climate states may also add errors. For example, the assumption of stationarity in the biases does not consider variations in albedo (e.g., glacier extension and vegetation) and near-surface fluxes and moisture (Velasquez et al., 2020) from the PI to the 21 ka BP.”

30. **357**: superscript “2” for the unit of area.

A: OK

31. **Section 4.5**: A seasonal view is missing and need here.

A: A discussion about summer and winter condition was extended, in particular in relation with the work of Velasquez et al. (2022).

32. **Fig. 6**: The 50% sea ice line is rather far south compared to newer estimates by Tierney et al. 2020. Maybe use these ones in the graph.

A: To our knowledge and according to Cauquoin et al. (2023), the reconstruction of Tierney et al. (2020) provides annual mean SST, without a mapped sea ice distribution. However, we found a newer sea ice extent map in Paul et al. (2020) which shifts the sea ice margin further north, in accordance to the reviewer observation. Text and figure 7 were modified accordingly.

33. **Section 4.5**, e.g., L450 but also elsewhere in the discussion: The authors need to discuss their results with existing literature, e.g., Velasquez papers and Ludwig papers. So, what it new, different, confirms compared to these studies, if different why is it different?

A: In order to implement the discussion, as suggested by the reviewer, several citations were added to section 4.5, together with some text:

- "The overall cooling and drying over Europe during the LGM are a typical response of LGM climate model simulations (e.g., Ludwig et al., 2017; Stadelmaier et al., 2021; Velasquez et al. 2021)."
- "This wind pattern supports the hypothesis of Kuhlemann et al. (2008) of more frequent and/or persistent polar air outbreaks over the western Mediterranean, causing recurring cyclogenesis over the Gulf of Genoa. In agreement with Kuhlemann et al. (2008) and differently from other climate model studies (Laîné et al., 2009; Velasquez et al, 2022), our simulations do not support a pure zonal and generally drier LGM atmospheric circulation south of the Alps, but identify an alternance of winter and summer conditions. Also, Ludwig et al. (2016) reported for Southern Europe more frequent westerly and cyclonic circulation weather types compared to the PI, and Ludwig et al. (2018) suggest that the region, particularly the Gulf of Genoa, was wetter compared to Central Europe and to adjacent periods. Our results show that in the southern sector of the Po plain towards the northern Apennines, a wide area of positive winter precipitation anomaly (Fig. 4) is likely linked to stau effects and orographic precipitation due to frequent easterly-northeasterly Bora wind events (Ludwig et al. 2021)."
- "This contradicts the findings of Velasquez et al. (2021; 2022) who, analysing high-resolution LGM climate simulations over the Alps, obtained significantly heavier precipitation rates during winter than during summer, with maxima in the Western Alps. Winter precipitation anomalies in both Velasquez's et al. (2021; 2022) and our study present negative values north of the Alps and positive values in the south. Conversely, differently from Velasquez et al. (2021; 2022), during summer we find a positive precipitation anomaly in the southern part of the domain (Fig. 4). This result suggests increased convection and cyclonic circulation in the northern Tyrrhenian region at 21 ka BP. The discrepancies with Velasquez et al. (2022) are possibly caused by differences in the driving GCM, the way convection is represented in the RCMs, and the bias correction applied in this study. In addition, also during the colder months, lee-side cyclones in the Tyrrhenian Sea lead to heavy precipitation in the southern Alpine slopes (Fig. 5, 7). Similarly, Ludwig et al. (2016) found only a slight decrease in precipitation occurring during the LGM south of the Alps, which was explained by enhanced LGM cyclonic activity compensating the reduced precipitation from other circulation weather types."

34. **L455**: Something similar is already shown in Raible et al. 2020 and this was a review so please be clear what is new and what you confirm.

A: OK. We added this review to the reference list. Nevertheless, when dealing with Genoa low and Mediterranean smaller scale circulation many other papers could be mentioned. In this brief final section, we just present a concise summary of the discussion about the main aspects that were probably topical in generating increased precipitation in the southern side of the Alps.

35. **Section 5**: The first two paragraphs are a summary rather than a conclusion. The last paragraph is rather general conclusion, so I suggest to be more specific.

A: We removed the first sentence of the second paragraph an added this: "We suggest that the seasonal variation of sea-ice extent was an important mechanism modulating the LGM southward shift of the westerlies.

Our work represents also the first application of the RegCM4 model to palaeoclimate studies over the Alps. Thus, we provide a new dataset composed of climate and envELA information, which can be employed in future studies of the LGM and PI-LIA."

- **Julien Seguinot - referee #1**
    - There remain several typos in the text especially on author names (Becker, Imhof, Velasquez) and other inconsistencies such as using "et al." for a single author reference. I think it is important to fix these inconsistencies before publication but leave this for the typesetting stage.

A: OK

- Eqn. 3 units are still missing. I did not understand the authors' response to my comment with a single reference to "Ohmura and Boettcher (2018)." Eqn. 3 links temperature and precipitation via numerical constants, but without knowing the units or the constants, or if temperatures are in °C or K and precipitation in kg or mm, it is impossible to interpret the equation.

A: We added at l 161: "P_{corr19} is expressed in millimetres and T_{ELA} in degrees Celsius. The standard error of the method is 648 mm."

- I find fig. S5 very useful, perhaps even more useful that the envELA map included in the paper (fig. 5). By showing the difference between the DEM and envELA (i.e. right part in Eqn. 4) it becomes much more clear which parts of the mountain range are prone to ice build-up. I would suggest to include it in the main text.

A: OK, it is the new fig. 6.b (all other figure numbers were adjusted accordingly)

- I actually preferred the previous (shorter) title without "the last phase of the LGM". The intro and methods now make it clear which period(s) you focus on (this was one critic in my previous review), so I don't think the longer title is needed.

A: We would prefer to maintain the title: 'Atmosphere-cryosphere interactions during the last phase of the LGM (21 ka BP) in the European Alps', which provides a more explicit reference to the time period studied, as also suggested by another referee.

Anonymous referee #3

General

The study is well structure and well written. The overall topic of the study is interesting and certainly valuable enough to be published, although it seems to be sometimes that the authors do not take enough caution on what we know so far and what is newly found be the authors. I would say that the authors mainly confirm existing knowledge also form the other model studies. Still, a confirmations of other modelling result is important so This is why I support this study. Given some of my comments below I recommend to publish this manuscript after major revisions.

A: Through the text, we added several citations and tried to be clearer about what was newly found by us and what was already known. It is true that some aspects related to our model output confirm other model studies. This was used to validate our simulations before reconstructing the envELA. Indeed, ~~The~~the main outcome of this work is the envELA reconstruction~~ and the~~. The manuscript represents the first reconstruction of the envELA for the LGM over the whole Alpine range. The most notable outcome relates to existing geomorphological evidence, addressing several issues existing in previous ELAs reconstruction.

Furthermore, t~~To~~o calculate the envELA we use LGM and PI simulations run with the RegCM4 model, which has never been used in a paleoclimate study in the Alpine region before. Thus, we provide a new dataset that can be employed in future studies. ~~The results of our climate simulation are in accordance with other model studies, something that was used to validate our simulations before reconstructing the envELA.~~

1. In particular, the discussion needs to substantially improved.

~~A: Owing the focus of this manuscript, we particularly focused the discussion section on the envELA. Nevertheless, we~~A: We now expanded section 4.2 (limitations of the method) and 4.5 (Atmospheric circulation), as suggested by the reviewer in the next comments.

2. Also, a more detailed analysis of the seasonality is needed, to compare with existing literature. The effect of the bias correction is not well treated and a comparison between simulation and proxy records is missing.

A: We expanded the results and discussion sections related to a comparison with proxy records and the seasonality of the atmospheric circulation. Winter and summer subplots for precipitation and precipitation anomaly were added as well.

~~Again~~However, since~~,~~ the main goal of this paper is the envELA reconstruction, which is based on yearly precipitation and summer temperature, we tried to keep the new analysis concise, as a~~. A~~n extremely detailed ~~punctual~~ seasonal analysis of the climate variables over the whole domain is ~~therefore~~ beyond our scope.~~.~~

~~Climate data were presented in the results to support the envELA calculation, while the atmospheric circulation was analysed in relation to some glacier basins (fig 4 and related discussion) and the potential interaction with the cryosphere. A more extended analysis and related broad discussions of seasonality of climate variables, which are for sure interesting, would require an independent paper.~~

Comments

3. **L12**: Please add a comma after "Here"

A: OK

4. **L34**: superscript "2" for the unit of area.

A: OK

5. **L45**: There is a new estimate for temperature change between LGM and PI: Annan, J. D., Hargreaves, J. C., and Mauritsen, T.: A new global surface temperature reconstruction for the Last Glacial Maximum, Climate of the Past, 18, 1883–1896, https://doi.org/10.5194/cp-18-1883-2022, 2022.

A: OK

6. **L50**: Please add the following review paper here: Raible, C. C., J. G. Pinto, P. Ludwig and M. Messmer, 2020: A review of past changes in extratropical cyclones in the northern hemisphere and what can be learned for the future, WIREs Climate Change, 12, e680. https://doi.org/10.1002/wcc.680

A: OK

7. **L55**: I think the references are misplaced here as they reconstruct the alpine ice cap during LGM – all the dynamical interpretation are hypotheses in these papers so maybe cite Raible et al. 2020 or other modelling-based papers, e.g. Ludwig et al. 2016, 2017

A: This is true. We added Ludwig et al. (2016). However, also Raible et al. (2021~~0~~) cited Luetscher et al. (2015) and Florineth and Schlüchter (2000) when talked about Alpine ice build-up.

8. **L71**: I think, the authors need to include a paragraph on regional modelling for LGM times, as the presented study is not the first of its kind. Important publications are Ludwig et al 2016,2017, Velsaquez et al 2020, 2021, 2022, Pinto and Ludwig 2020 mentioned later in the manuscript.

A: ~~Pinto and Ludwig (2020) was already cited at line 48, while Ludwig et al. (2016) is about global climate models ((i) CCSM4 [Gent et al., 2011], (ii) MIROC-ESM [Sueyoshi et al., 2013], (iii) MPI-ESM-P [Jungclaus et al., 2013; Stevens et al., 2013], (iv) MRI-CGCM3 [Yukimoto et al., 2012]).~~

As suggested by the reviewer, t~~This~~his paragraph was added: "In recent years, the number of studies using RCMs for palaeoclimatic applications has notably increased, providing much information about the LGM circulation in the North Atlantic and Europe. For example, Ludwig and Pinto (2020) explored the extratropical cyclones in the North Atlantic region; Shaffernicth et al. (2020) and Ludwig et al. (2021) analysed high-~~-~~resolution climate simulations to study dust cycles and loess deposition; Imhof (2021) forced a hybrid ice sheet model with high-resolution (2 km) climate data to model the LGM Alpine ice fields; and Ludwig et al. (2017) and Velasquez et al. (2021, 2022) studied the role of sea surface temperatures, vegetation and ice-sheet topography in the Alpine climate during glacial times (LGM and MIS4).“

9. **L72**: Please add a comma after “Here”

A: OK

10. **L81**: Please add Kuhlemann et al. 2008 here.

A: OK

11. **Section 2.2**: Please define the domain in 50 km resolution and maybe show it in a figure together with the 12 km resolution.

A: W~~we~~e added the extension of the 50 km resolution domain in the main text (“The lower-resolution RegCM4 simulations (50 km) extend from 3.8 to 23.0 °E, and 37.5 and 51.0 °N~~...”),~~,...”) and a figure (Fig. S1) in the supplementary materials.

12. **L130**: I do not understand why the authors only include the horizontal extent of the ice sheet and not the height. In Seguinot et al. 2018 they could have made use of a 3 dim estimate of the alpine ice cap.

A: We ~~already~~ added explanations for this choice after the first round of review:

- 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 (2021) and Velasquez et al. (2022) highlighted the importance of including glaciers’ topography into global and regional palaeoclimate models.”
- 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 approach might introduce some uncertainty in the envELA estimations."

In this regard, to further clarify this aspect, we added an additional explanation in the paragraph 4.2 after the [*], as follow: “This is in contrast with the approach followed by Merz et al. (2015), Imhof (2021) and Velasquez et al. (2022). However, differently from us, these studies are based on climate data at a much higher resolution (2 km for Imhof, 2021 and Velasquez et al., 2022) or focused on regions with a very different topography compared to the Alps (Laurentide Ice Sheet and North Atlantic for Merz et al., 2015), where, at the LGM, the ice build-up generated a 4000 m high orographic barrier over a previously ice-free region. Conversely, at the LGM the Alps were characterized by ice domes and valley glaciers (Kelly et al., 2004; Ivy-Ochs et al., 2022) generally narrower than our model resolution (12 km) and they did not strongly modify the main alpine range profile.”

13. **L134**: Given the importance of the vegetation changes it would be good to see how the constructed vegetation cover looks like.

A: Here, a figure representing the vegetation and two tables to clarify how the bioma are structured. We added a reference (Del Gobbo, 2021) where one can find these figure and tables and some explanations, based on extensive existing literature.

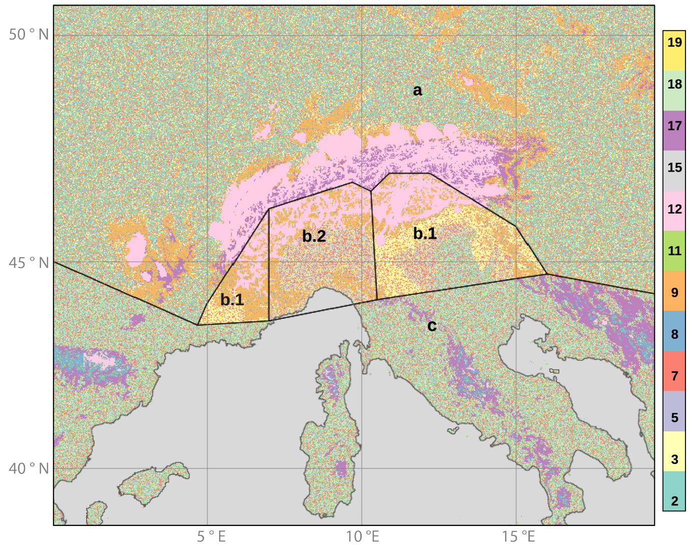

Figure R1: Reconstructed vegetation map. The black lines identify three sub-regions: (a) northern Alpine, (b.1) southwestern and eastern Alps, (b.2) West Garda Sector, and (c) Pyrenees, Apennines and Balkans. Each region is further divided into altitudinal bands chosen specifically for each area (Tab. 1). Every plant type is defined according to its corresponding BATS code (Tab. 2; Wilson et al., 1987), as shown in the colour bar on the right. Glaciers are in pink. The percentage of every plant type for each sub-region and altitudinal band is shown in tables 1 and 2.

Regions		Bioma	Altitudinal Bands
Northern Alps		Boreal Steppa	0 to 700 m
		Forest - Tundra	700 to 800 m
		Tundra	800 to 1200 m
		Desert	> 1200 m
Southern Alps	Western and Eastern Sector	Steppa	0 to 110 m
		Steppa - Forest	110 to 130 m
		Boreal Forest	130 to 700 m
		Forest - Tundra	700 to 900 m
		Tundra	> 900 m
	West Garda Sector	Steppa	0 to 110 m
		Steppa - Forest	110 to 700 m
		Forest - Tundra	700 to 900 m
		Tundra	> 900 m
Mediterranean		Steppa	0 to 900 m
		Tudra	900 to 1500 m
		Desert	> 1500 m
North Africa		Steppa - Forest	0 to 300 m and 1200 to 1500 m
		Temperate Forest	300 to 120 m
		Steppa	> 1500 m
Desert		Steppa	1000 to 1500 m
		Desert	0 to 1000 m and > 1500 m

Table R1: Subdivision of every region into altitudinal bands and the corresponding bioma

Bioma	Plant Type	%	BATS	CLM
Steppa	Short Grass	20	2	14
	Deciduous Broadleaf Tree	10	5	8
	Semi-Desert	15	11	1, 14
	Deciduous Shrub	35	17	11
	Tall Grass	20	7	14
Boreal Steppa	Short Grass	35	2	13
	Tall Grass	15	7	13
	Deciduous Broadleaf Tree	10	5	9
	Semi-Desert	10	11	1, 13
	Evergreen Needleleaf Tree	10	3	3
	Tundra	10	9	12, 13
	Deciduous Shrub	10	17	12
Steppa-Forest	Deciduous Broadleaf Tree	20	5	8, 9
	Tall Grass	25	7	13, 14
	Deciduous Shrub	25	17	11, 12
	Mix Woodland	15	18	2, 3, 4, 8, 9, 10, 11, 12
	Forest/Field	15	19	2, 3, 4, 8, 9, 10, 11, 12, 13, 14
Temp. Forest	Deciduous Broadleaf Tree	20	5	8
	Tall Grass	15	7	14
	Deciduous Shrub	10	17	11
	Mix Woodland	20	18	2, 4, 8, 10, 11
	Forest/Field	10	19	2, 4, 8, 10, 11, 14
	Evergreen Neadleleaf Tree	25	3	2
Boreal Forest	Evergreen Needleleaf Tree	40	3	3, 4
	Tall Grass	20	7	13
	Deciduous Shrub	10	17	12
	Mix Woodland	20	18	3, 9, 10, 12
	Forest/Field	10	19	3, 9, 10, 12, 13
Forest-Tundra	Evergreen Needleleaf Tree	25	3	3, 4
	Tundra	50	9	12, 13
	Deciduous Shrub	10	17	12
	Evergreen Shrub	10	9	12
	Deciduous Broadleaf Tree	5	5	9
Tundra	Desert	10	8	1
	Tundra	80	9	12, 13
	Semi-Desert	10	11	1, 13
Desert	Desert	80	8	1
	Semi-Desert	20	11	1, 13
Glaciers	Glaciers	100	12	1
Ocean	Ocean	100	15	1

Table R2: Percentages of plant types per every bioma with the corresponding BATS (Wilson et al., 1987) and CLM codes (Oleson et al., 2013).

14. **Section 2.4**
    a. Why is a bias correction needed. The authors destroy a bit the physical connection between precipitation and temperature. Would the results change if the not bias corrected is used to estimate ELA.

A:

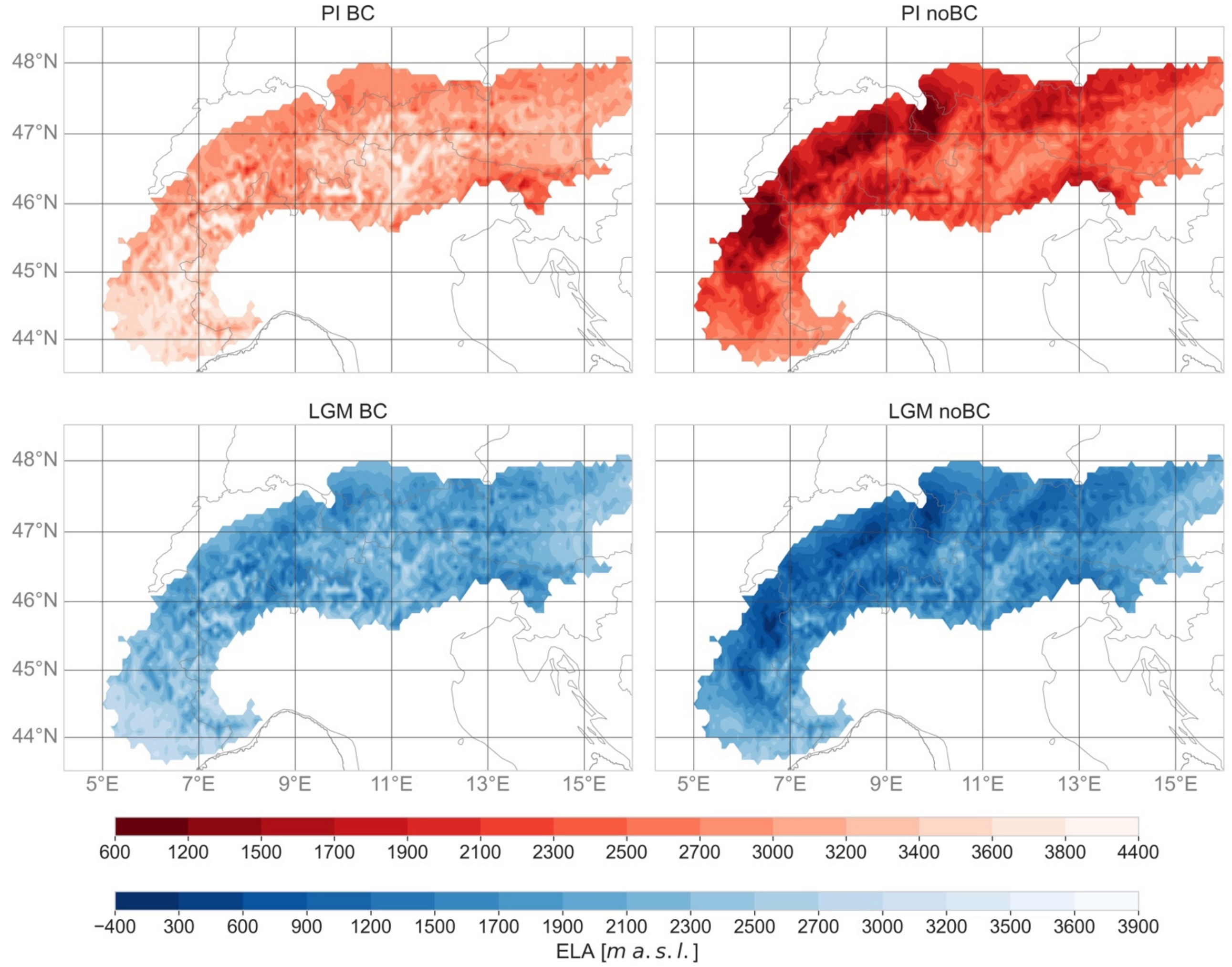

Figure R2: envELA calculated from PI (first row) and LGM (second row) bias-corrected (BC) and non-bias-corrected (noBC) RegCM4.

Yes, it changes (Fig. R2). The average difference of the envELA calculated with bias and non-bias-corrected data over the Alps, ranges between 450 and 900 m on average. Western Alps show particularly low envELA values, when no bias correction is applied (darker colours in fig. R2). After the analysis of pre-industrial simulation (PI) vs historical observations (LaPrec and HISTALP 1871-1900) and despite the expected tuning performed before running the simulations, it was evident that the model had a wet bias in the precipitation, which is particularly strong on the western Alps (fig. S3), and a cold bias in summer temperature over all the domain and on the Alps all year round (fig. S2). In general, biases in temperature and precipitation are considered normal in climate modelling also at the highest resolution of convection-permitting.

We added two paragraphs:

- in the introduction: “However, regardless of the fine scale of RCMs, the simulated precipitation patterns can still show substantial biases (Ban et al., 2014; Velasquez et al., 2020; Gómez-Navarro et al., 2018; Casanueva et al., 2016; Rajczak and Schär, 2017) which may affect hydrological and glacier models being forced by RCM data (e.g., Imhof, 2021; García-Valdecasas Ojeda et al., 2022). Thus, a bias-correction can be required in order to correct RCM errors (Velasquez et al., 2020)."

- In the methods: "Despite the fine resolution used and the model customization, biases can still affect RCM output data due to initial and boundary conditions from the driving GCM (the MPI-ESM-P is characterized by a northward shift of the upper-level North-Atlantic jet stream; Ludwig et al., 2017) as well as the parameterization of processes occurring at finer scales than the simulations' resolution (Velasquez et al, 2020). Since we need absolute temperature and precipitation values to reconstruct the envELA, we thus applied a first-order bias correction to our data, in order to account for model biases such as a cold bias in temperature over the Alpine range and a wet bias in precipitation over the western Alps (fig. S2 and S3)."

We stress that this work represents the first reconstruction of the envELA for the LGM over the whole Alpine range, and, according to geomorphological data, better resolves different regions where previous model studies showed several issues. However, for sure, future improvements can be carry out as different assumptions and simplification were made.

b. Also, it would be good to show the biases in temperature and precipitation.

A: Figures S2 and S3 were added, showing PI temperature and precipitation (yearly, DJF and JJA) for non-bias-corrected RegCM4 data, bias-corrected RegCM4 data, and the bias between PI non-bias-corrected RegCM4 data and observations.

c. I also would like to mention that the observations strongly underestimate precipitation in complex and high terrain (Frei et al. papers), so maybe the model is even more realistic in that variable using the not corrected values.
    i. Frei, C. and Schär, C.: A precipitation climatology of the Alps from high-resolution rain-gauge observations, Int. J. Climatol., 18, 873–900, https://doi.org/10.1002/(SICI)1097-0088(19980630)18:8<873::AIDJOC255>3.0.CO;2-9, 1998.
    ii. Frei, C., Christensen, J. H., Déqué, M., Jacob, D., Jones,R. G., and Vidale, P. L.: Daily precipitation statistics in regional climate models: Evaluation and intercomparison for the European Alps, J. Geophys. Res.-Atmos., 108, 4124, https://doi.org/10.1029/2002JD002287, 2003

A: OK, we mentioned this aspect and cited Frei and Schär (1998) in the discussion (section 4.2).

15. **L156**: Please change methodology to Method throughout the text as both words have a different meaning.

A: OK

16. **L168**: The authors assume a constant lapse rate but the lapse rate will change rather strongly between LGM and PI so I suggest to calculate the lapse rate from each model simulation (PI and LGM separately) and use this to estimate the envELA.

A: We calculated the summer lapse rate over the Alpine range for LGM and PI from our simulations which resulted in 0.7 °C/100m for the bias-corrected LGM and 0.56 °C/100m for the bias-corrected PI and observations. Compared to the literature PI/OBS lapse rate are too low by 0.09 °C/100m (Figure ~~R4~~R3). Calculating the envELA with the different lapse rate, we obtain a difference of 45 m (283 m) for the LGM (PI), which fall in the range of error of the method.

Considering these elements, we prefer to use the value of 0.65 °C/100m. We also chose to be consistent with the first existing work on this topic (Žebre et al., 2021) that uses the same lapse rate to calculate the envELA till 2100, under different RCP scenarios (RCP2.6, RCP4.5, and particularly RCP8.5).

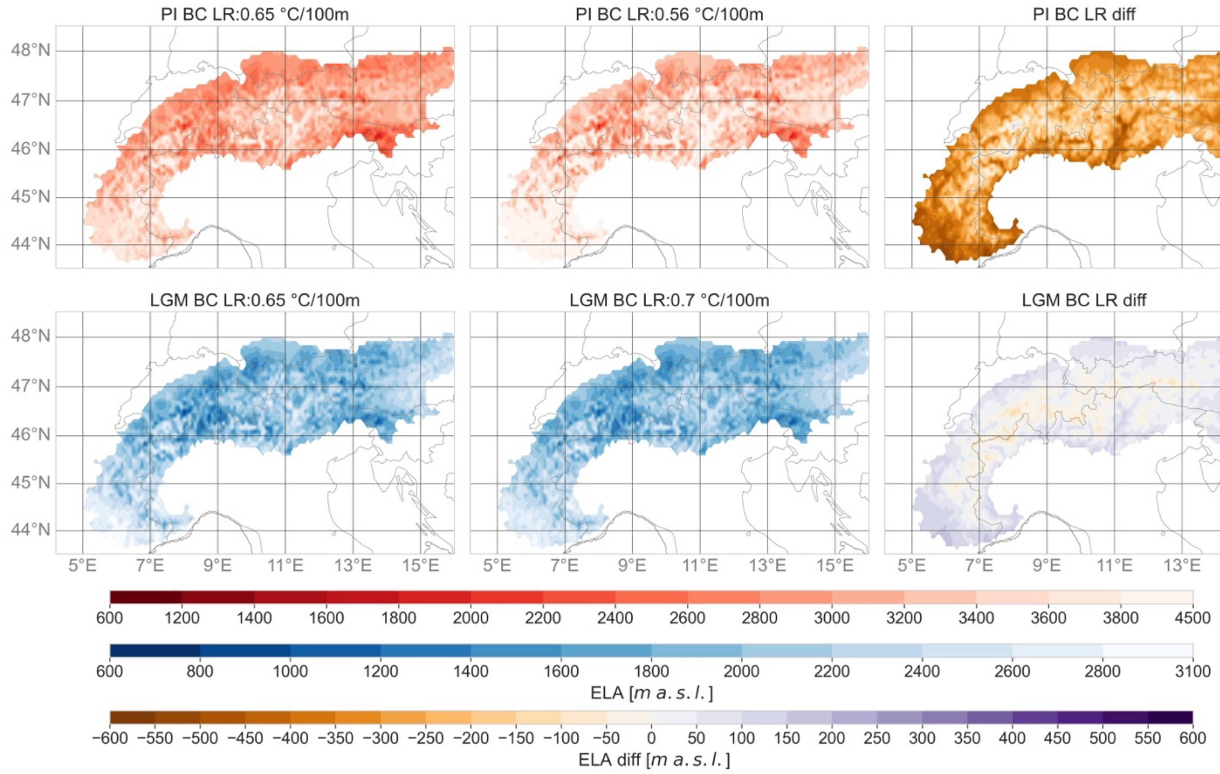

Figure R3: PI (first row) and LGM (second row) envELA calculated with different lapse rate and their difference.

17. **L188**: In Ludwig et al. 2017 the authors showed that the MPI ESM simulations has a rather strong biases in the North Atlantic so was this here corrected? At least this needs to be mentioned that there are also biases in the driving GCM.

A: We applied the bias-correction on the RegCM4 simulations and we added:

- in the methods (section 2.1): "*The MPI-ESM-P has already been successfully employed in the study of the LGM (e.g., Pinto and Ludwig, 2020; Stadelmaier et al. 2021), showing a northward shift of the upper-level North-Atlantic jet stream when compared with the multi-model mean of the CMIP5/PMIP3 and CMIP6/PMIP4 projects (Kageyama et al., 2021). This behaviour is possibly associated ~~to~~ with a strong influence of the Scandinavian ice sheet in Central Europe. Overall, however, the behaviour of the MPI-ESM-P is in line with that of other models (Ludwig et al., 2016) and, given the agreement of this model with proxy records (permafrost and ground cracking extent; Stadelmaier et al. 2021) we can assume that the LGM large-scale circulation is represented in a reasonably accurate way by the MPI-ESM-P, thereby providing realistic forcing data for the RegCM4.*";
- and in the section 3.1 of the results: "...*although the LGM upper-level North-Atlantic jet stream is stronger over the northern parts of the North Atlantic compared to other models (Ludwig et al., 2016).*"

18. **L204**: Are DJF really the coldest months, not that insulation has changed.

A: Yes, they are. According to our data, ~~At~~at the LGM on the Alps the difference between February and March temperature is smaller than at the PI, but February was always colder than March.

19. **L216**: Compared to the driving GCM (9C the 6.6C temperature response is substantially weaker, why is that. I would have expected an even stronger response as orography is between resolved in the RCM than the GCM?

A: Because the 9 °C anomaly refers to the whole central Europe, thus to a broader region compared to the area where 6.6 °C were calculated, i.e., the domain of the RegCM simulations. The GCM data is influenced by the proximity of the Scandinavian Ice Sheet, which causes lower average temperature. However, as hypothesized by the ~~Reviewer~~reviewer, considering only the Alps, the temperature anomaly is stronger in the RegCM than in the GCM.

20. **L235-239**:

   a. The dynamics might have changed if the authors would have implemented an ice cap so at least a more cautious discussion is needed.

~~A:~~ We replied to this comment above~~See also comment to line 130. Here (L235-239), we only present our results. We wrote about ice topography issues in the methods and in the limitation section of the discussion. To summarize, due to the topography smoothing in the RegCM4 and the model relatively coarse resolution we did not include ice thickness in the simulations.~~

, line 130.

   b. Also, the level of detail (going down the level of single glaciers) is too superficial given the resolution of 12 km.

A: The analysis of ll235-239 is obtained not studying a single cell of 12 km for each glacier but studying a larger region surrounding the glacier basin (shown in new fig. 5).

   c. Please check the later comment throughout the manuscript.

Later in the text (section 4.3) we compare the envELA with effELA from other studies, but we also stress on the difference between these two types of ELAs. The envELA has the characteristic of being regional and climatic and for this reason was provided as range of values rounded every 50 meters. A comprehensive discussion about this aspect is given in Žebre et al. (2021), sections 4.1 (environmental vs effective ELA), 4.2 (model uncertainties), 4.3 (link between envELA and historical observations of glaciers fluctuations). In particular, in that paper the authors reported that *"… the envELA is ~ 75–150 m higher than the regional effELA when averaged over a longer climate period, e.g. 15–30 years. The difference between envELA and wgmsELA might also be related to the fact that the glaciers selected for measuring annual glacier mass balance by the WGMS are those with easier access and thus tend to be located on lower altitudes, consequently having on average lower ELAs. While the envELA is consistently higher than effELA, the time series pattern is in general well reproduced (Fig. 9)…".9)…"*. For convenience we copy and paste figure 9 and 10 of Žebre et al. (2021) with captions.

~~(e.g, "…*For example, Colucci (2016) placed the ELA [effELA] 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. [envELA]*…").~~

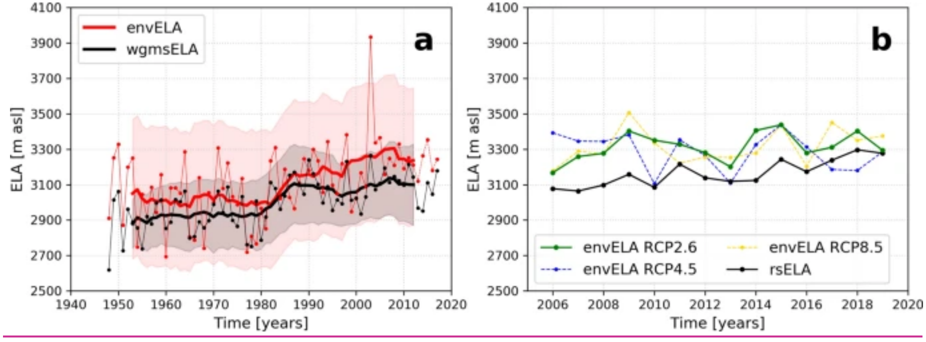

Figure R4: **a** Comparison between the envELA averaged over the grid cells as defined in Fig. 11 and average regional wgmsELA for 62 glaciers for the period 1948–2017. The last 12 years (2006–2017) of the envELA (dashed line) represent average of all three RCPs envELAs. Thick lines correspond to 11-year centred running mean, thin lines represent yearly variations, and transparent bands correspond to the standard error of Eq. 3 (i.e.3 (i.e. 648 mm) for the envELA and sample standard deviation for wgmsELA. (b) Comparison between the rsELA derived from Landsat images and envELA derived from climate projections under three different scenarios (RCP2.6, RCP4.5 and RCP8.5) for the period 2006–2019 over the rsELA extent as defined in Fig. 1.1.

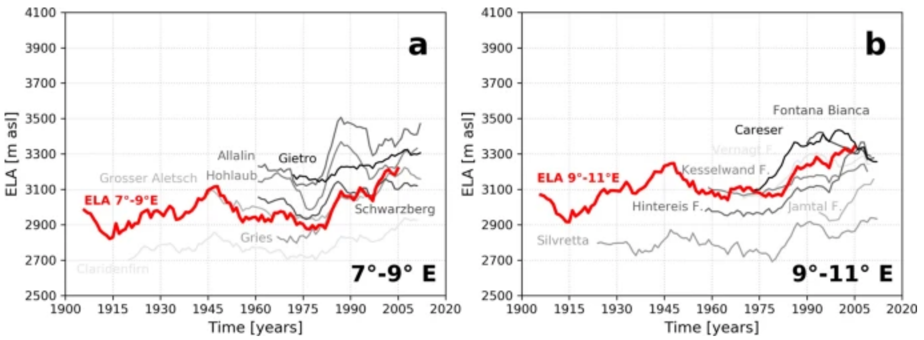

Figure R5: The wgmsELAs of 14 glaciers located in the sectors **a** between 7° and 9°E longitude and **b** 9° and 11°E longitude. Lighter lines equate to northern located glaciers and darker lines to southern located glaciers. In red is the envELA averaged over that same sector. All ELAs are presented as 11-year centred running means.

21. **Fig. 1**: Please show only precipitation and wind arrows. The other lines are making the plots too busy. Also note that temperature and precipitation will be shown also in Fig. 2 and 3.

~~A:~~ A: ~~This figure is meant to summarize the model outputs (without bias correction), giving a global idea of the circulation.~~ In order to make the figure tidier, as suggested by the reviewer, we split it in two parts. Now, in the first row there are winds and precipitation, in the second one geopotential height and temperatures. –This figure is meant to summarize the model outputs (without bias correction), giving a global idea of the circulation. ~~For this reason, we would like to keep all the elements together, from geopotential, to wind, and **not** bias-corrected temperature and precipitation.~~

We believe that it is important to keep also temperatures in this figure because ~~In~~in figure 2 (old figure 1) temperature and precipitation are not bias-corrected, differently from figures 3 and 4 (old figures 2 and 3).

22. **Fig. 3**: Please add DJF and JJA and discuss the seasonality of the signal in the manuscript. I think in one of Velasquez papers these authors see that in summer precipitation is reduced and in winter increased, which contradicts these results.

A: We added winter and summer PR to the figure. In the text we already mentioned winter and summer precipitation in section 3.2.2., but we added sone further analysis.

- Results: *"...with the most pronounced cooling and drying occurring in summer (-7.3 °C of cooling and -38.1 % of drying) [...] Summer anomalies are always more pronounced than winter anomalies in both regions ~~(Fig. 4)~~(Fig. 4)."*
- and discussion as: *"This contradicts the findings of Velasquez et al. (2021; 2022) who, analysing high-resolution LGM climate simulations over the Alps, obtained significantly heavier precipitation rates during winter than during summer, with maxima in the Western Alps. Winter precipitation anomalies in both Velasquez's et al. (2021; 2022) and our study present negative values north of the Alps and positive values in the south. Conversely, differently from Velasquez et al. (2021; 2022), during summer we find a positive precipitation anomaly in the southern part of the domain (Fig. 4). This result suggests increased convection and cyclonic circulation in the northern Tyrrhenian region at 21 ka BP. The discrepancies with Velasquez et al. (2022) are possibly caused by differences in the driving GCM, the way convection is represented in the RCMs, and the bias correction applied in this study."*

23. **F.2 and Fig3**: I am interested in the response between LGM and PI when no bias correction is introduced in particular for Fig. 3.

A: The difference between bias-corrected and non-bias-corrected anomalies for temperature is 0 (excluding the sea) (fig. ~~R4~~R6), as the same bias correction was applied to PI and LGM. For precipitation it varies with space, as the correction is multiplied to the model data (fig. ~~R5~~R7).

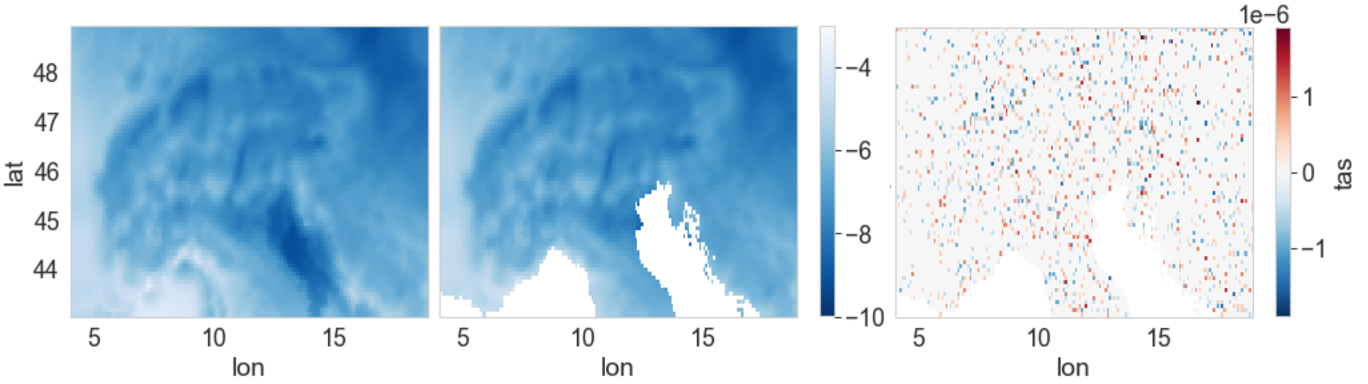

Figure ~~R4~~R6: LGM-PI temperature anomaly (in °C) without bias-correction (left) and with bias-corrected (centre). On the right the difference between the other two boxes.

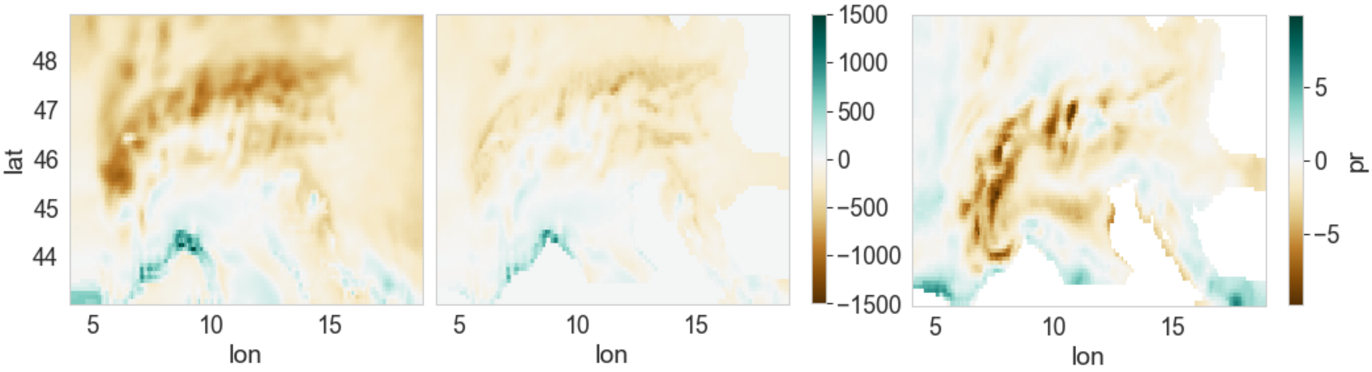

Figure ~~R5~~R7: LGM-PI precipitation anomaly (in mm) without bias-corrected (left) and with bias-corrected (centre). On the right the difference between the other two boxes.

24. **L267**: Please remove “can” here

A: OK

25. **Fig.4 and discussion of Fig. in the MS**: To me it is not clear whether you show wind direction and precipitation or wind direction under the condition that there is precipitation. The second one would make much more sense.

A: The reviewer is right; it is the second one. Fig. 5 and S4 labels have been updated: “21 ka BP (PI) seasonal wind origins associated to each of the 19 simulated years precipitation event. This has been done for Rhine, Inn-Salzach-Traun (IST), Tagliamento and Dora Baltea glacier subdomains. Windroses show the main wind directions under the condition that precipitation events occur. Colours represent precipitation intensity in millimetres and colour band width is the frequency of a given precipitation intensity per wind direction. The shadow in the map is the glacier extension (Ehlers et al., 2011), the colour lines as well as the full colour in the boxes represent the topography (yellow for higher elevation and green for the lowers) and the black line is the present-day political boundary.”

26. **Fig.5**: how would this figure look like if no bias correction is applied.

A: Please, see answer to comment about Section 2.4 and Fig. R2.

27. **L291-295**:
    a. I think the authors need to show a model-proxy comparison. Just saying that it is good is not sufficient.

A: Thanks, we realised this part was missing. We added this table in the supplementary (Tab. S1), that shows 21 ka BP - PI anomalies for our simulations, Wu et al. (2007), and Pini et al. (2022). And the following text: “*In the bias-~~–~~corrected domain, few proxies are available for evaluating the simulated climate (Wu et al., 2007; Pini et al., 2022). The RegCM4 data show cooler and drier conditions for 21 ka BP, in agreement with temperature and precipitation pollen-based reconstructions for the coldest and warmest months of the LGM (Wu et al., 2007). In line with other model studies, absolute values of simulated temperature and temperature anomalies underestimate proxy values (Pini et al., 2022). This is possibly caused by model shortcomings or by the higher proxy sensitivity to climate extremes than to climatological mean states (Kageyama et al., 2006; Velasquez et al, 2021).*”

		ΔT_{JAN}		ΔT_{JUL}		ΔP_{JAN}		ΔP_{JUL}	
LAT	**LON**	**Proxy**	**RegCM**	**Proxy**	**RegCM**	**Proxy**	**RegCM**	**Proxy**	**RegCM**
†47.73	6.5	-17.6	-9.5	-11.8	-5.1*	-17.0	-13.0	-23.7	-18.4
†45.67	4.89	-11.4	-7.7	-7.6	-5.4	-19.4	-1.5	5.3	5.6
‡45.27	11.74	-23.0	-10.2*	-9.6	-6.5*	/	/	/	/

Table R3: *21 ka BP-PI temperature and precipitation anomaly of January and July. The values are averaged over the 19 years of the RegCM4 simulations considering the nearest model grid point to the pollen site. Pollen-based reconstructions are from: Wu et al. (2007)† that provide a central value and a 95% confidence interval corresponding ±60 mm month^{-1} for precipitation anomaly, ±10–20 °~~°~~C for January temperature anomaly and ±3–5 °C ~~°~~for July temperature anomaly; and Pini et al. (2022)‡ whose error is 4.4 °C for ΔT_{JAN} and 2.0 °C for ΔT_{JUL}. * The value falls out of 95% confidence interval or the method error.*

b. Also show how the biases correction affects the results.

A: Please, see answer to comment about section 2.4 and Fig. ~~R2. tWe do not think that it is relevant to show in the paper also the non-bias-corrected envELA, which does not show a fit with geomorphological evidence. The difference between envELA calculated with bias-corrected and non-bias-corrected data is large~~R2~~.~~

28. **L315**: “In fact”

A: OK

29. **Section 4.2**: I suggest to include also a discussion on the effect of the bias correction and its limitation. The basic problem is that any bias method assumes stationarity, so that biases are independent from the state estimated. This might be OK for climate states not so different to the reference state but during the LGM the climate is very different so it might be problematic to apply such corrections.

A: ~~OK~~Thanks for the observation. This was now added in section 4.2: “In order to at least partially address these errors, a bias correction was applied to the RegCM4 output. However, further uncertainties can be introduced by calculating the correction function from limited observations, which may suffer from the rain gauge undercatch and the misrepresentation of high-altitude regions (Frei and Schär,~~;~~ 1998). In addition, the application of the same bias correction method to very different climate states may also add errors. For example, the assumption of stationarity in the biases does not consider variations in albedo (e.g., glacier extension and vegetation) and near-surface fluxes and moisture (Velasquez et al., 2020) from the PI to the 21 ka BP.”

30. **357**: superscript “2” for the unit of area.

A: OK

31. **Section 4.5**: A seasonal view is missing and need here.

~~A: A detailed seasonal analysis is beyond our scope, however a~~A: A ~~-~~discussion about summer and winter condition was extended, in particular in relation with the work of Velasquez et al. (2022).

32. **Fig. 6**: The 50% sea ice line is rather far south compared to newer estimates by Tierney et al. 2020. Maybe use these ones in the graph.

A: To our knowledge and according to Cauquoin et al. (2023), the reconstruction of Tierney et al. (2020) provides annual mean SST, without a mapped sea ice distribution. However, we found a newer sea ice extent map in Paul et al. (2020) which shifts the sea ice margin further north, in accordance to the reviewer observation. Text and figure 7 were modified accordingly.
~~I am not sure which publication the reviewer is referring to. From Tierney et al. (2020) we found:~~

- ~~Tierney, J. E., Poulsen, C. J., Montañez, I. P., Bhattacharya, T., Feng, R., Ford, H. L., ... & Zhang, Y. G. (2020). Past climates inform our future. *Science*, *370*(6517), eaay3701.~~
- ~~Tierney, J. E., Zhu, J., King, J., Malevich, S. B., Hakim, G. J., & Poulsen, C. J. (2020). Glacial cooling and climate sensitivity revisited. *Nature*, *584*(7822), 569-573.~~

~~But we cannot find the sea ice margin in any figures. In the second manuscript there is only the ice sheet extent in figure 1. Maybe we missed the paper the reviewer meant.~~

~~32.~~33. **Section 4.5**, e.g., L450 but also elsewhere in the discussion: The authors need to discuss their results with existing literature, e.g., Velasquez papers and Ludwig papers. So, what it new, different, confirms compared to these studies, if different why is it different?

A: ~~Our work is not focused on the atmospheric circulation. Climate data are essential in the study but our main goal is the envELA reconstruction. A deep study of the atmospheric circulation is beyond our scope. However, many~~In order to implement the discussion, as suggested by the reviewer, several citations were added to section 4.5, together with some text:

- "The overall cooling and drying over Europe during the LGM are a typical response of LGM climate model simulations (e.g., Ludwig et al., 2017; Stadelmaier et al., 2021; Velasquez et al. 2021)."
- "This wind pattern supports the hypothesis of Kuhlemann et al. (2008) of more frequent and/or persistent polar air outbreaks over the western Mediterranean, causing recurring cyclogenesis over the Gulf of Genoa. In agreement with Kuhlemann et al. (2008) and differently from other climate model studies (Laîné et al., 2009; Velasquez et al, 2022), our simulations do not support a pure zonal and generally drier LGM atmospheric circulation south of the Alps, but identify an~~d~~ alternance of winter and summer conditions. Also, Ludwig et al. (2016) reported for Southern Europe more frequent westerly and cyclonic circulation weather types compared to the PI, and Ludwig et al. (2018) suggest that the region, particularly the Gulf of Genoa, was wetter compared to Central Europe and to adjacent periods. Our results show that in the southern sector of the Po plain towards the northern Apennines, a wide area of positive winter precipitation anomaly (Fig. 4) is likely linked to stau effects and orographic precipitation due to frequent easterly-northeasterly Bora wind events (Ludwig et al. 2021)."
- "This contradicts the findings of Velasquez et al. (2021; 2022) who, analysing high-resolution LGM climate simulations over the Alps, obtained significantly heavier precipitation rates during winter than during summer, with maxima in the Western Alps. Winter precipitation anomalies in both Velasquez's et al. (2021; 2022) and our study present negative values north of the Alps and positive values in the south. Conversely, differently from Velasquez et al. (2021; 2022), during summer we find a positive precipitation anomaly in the southern part of the domain (Fig. 4). This result suggests increased convection and cyclonic circulation in the northern Tyrrhenian region at 21 ka BP. The discrepancies with Velasquez et al. (2022) are possibly caused by differences in the driving GCM, the way convection is represented in the RCMs, and the bias correction applied in this study. In addition, also during the colder months, lee-side cyclones in the Tyrrhenian Sea lead~~s~~ to heavy precipitation in the southern Alpine slopes (Fig. 5, 7). Similarly, Ludwig et al. (2016) found only a slight decrease ~~of~~ in precipitation occurring during the LGM south of the Alps, which was explained by enhanced

LGM cyclonic activity compensating the reduced precipitation from other circulation weather types."

~~33.~~34. **L455**: Something similar is already shown in Raible et al. 2020 and this was a review so please be clear what is new and what you confirm.

A: OK. We added this review to the reference list. Nevertheless, when dealing with Genoa low and Mediterranean smaller scale circulation many other papers could be mentioned. In this brief final section, we just presented a concise summary of the discussion about the main aspects that were probably topical in generating increased precipitation in the southern side of the Alps.

~~34.~~35. **Section 5**: The first two paragraphs are a summary rather than a conclusion. The last paragraph is rather general conclusion, so I suggest to be more specific.

A: We removed the first sentence of the second paragraph an added this: "We suggest that the seasonal variation of sea-ice extent was an important mechanism modulating the LGM southward shift of the westerlies.

Our work represents also the first application of the RegCM4 model to palaeoclimate studies over the Alps. Thus, we provide a new dataset composed of climate and envELA information, which can be employed in future studies of the LGM and PI-LIA."