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Interactive comment on "Modelling last glacial cycle ice dynamics in the Alps" *by* Julien Seguinot et al.

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Dear Anonymous Referee #2,

Thank you very much for your detailed review of our manuscript.

General comments

This manuscript describes a model study with the Parallel Ice Sheet Model applied to the last glacier cycle in the Alps. The climate forcing is derived from present day climate of WorldClim and the ERA-Interim reanalysis and time-dependent temperature offsets derived from the Greenland Ice core (GRIP), from Antarctic ice core (EPICA)

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and Marine sediment core from the Iberian margin (MD01-2444). The study is split in two, in the first part analysis of six model simulations (with and without precipitation scaling) made on a 2 km resolution grid is presented and concluded that out of the three climate forcing records used, the EPICA record gives the most realistic ice volume history during MIS 4 and 2. The second part analyses simulation made with the EPICA forcing record on a 1km grid. The authors draw conclusions about the ice cover, ice flow pattern, ice thickness, LGM ice extent, which in their model is a transient stage with varying timing across their model domain due to glacier dynamics.

Thank you very much for this fully accurate summary.

The manuscript is well organized and clearly written, the missing thing in this study is a discussion of and preferably a sensitivity study of the ice dynamic-model assumptions made. Is the sliding of the ice age ice sheet realistically modelled with pseudo-plastic assumption using the Shallow Shelf approximation? How sensitive are the results to the selected model parameters? It is briefly mentioned once on page 19, line 8, but a thorough analysis of the model sensitivity would strengthen the paper.

Thank you. We agree that a sensitivity study to ice physics, in particular basal sliding, is one of many improvements needed upon our results. However, for the kind of exercise presented here, the sensitivity to palaeo-climate history, which is virtually unknown and has many degrees of freedom, far outweight the model sensitivity to ice physics. From the perspective of glacial geology, a 5 K change in air temperature is more influential than an order-of-magnitude increase in ice velocities (perhaps with the exception of our conclusions on trimlines, see below). In its current state, our manuscript studies the model sensitivity to the primary source of uncertainty, which is climate.

Because the simulations presented here depend on computing resources only available through a peer-review application process, we are currently unable to perform an additional sensitivity study on basal sliding for the entire Alps. However, a regional study on the model sentivity to basal sliding is actually the topic for a follow-up study

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currently under preparation for the Rhine Glacier (Imhof et al., 2017), which has a relatively isolated catchment for its size as compared to other Alpine Glaciers.

Meanwhile, the following text was added in the section on trimlines, which is certainly the most sensitive aspect of our results to basal sliding:

> *The remaining discrepancies may relate to temporal migrations of the basal thermal boundary, an absence of sliding in warm-based areas, and levelling of small-scale topographic features in the 1 km horizontal grid. They call for more detailed comparisons spanning the entire Alpine range and specific sensitivity studies to relevant basal sliding and ice rheological parameters, and to the uncertain subglacial topography.*

In addition, basal sliding and other sources of uncertainties in ice physics where also mentioned in the conclusions:

> *However, these results are limited by uncertainties on ice physics. The till deformation model used here does not hold for sliding over bedrock surfaces. On the other hand, the constant friction angle used is representative of wet till but weaker basal conditions may have applied over saturated lake sediments where they occured. In the absence of ice deformation measuremets, a constant rheology was used for temperature ice containing more than 1 % of liquid water.*

Specific comments

I find missing something that indicates that the times are before present, as in line 5, line 8 and line 16 on page 1 – and elsewhere in the paper it is written (120-0 ka) should you add before present or BP to indicate the time interval?

We have now defined this better in the introduction:

> *During the last 800 ka (thousand years before present)*

Could the reason for too large ice volumes when using the GRIP record, as mentioned in lines 13-15 on page 9 be due to Arctic Amplification? Could that have an effect then as it has now? This is also mentioned in line 11 on page 10.

These passages refer to the Younger Dryas and Dansgaard-Oeschger events. One must keep in mind that a linear scaling was applied to the GRIP record, so that it is already "de-amplified" before being used as temperature forcing. But still, Arctic amplification could be an explanation if it was stronger then than for changes that lead the LGM climate. Although we lack expertise on this topic, we could not find literature supporting this idea. Instead, current theories for the Younger Dryas and Dansgaard-Oeschger events mostly involve large amounts of freshwater discharge into the North Atlantic implying a more regional mechanism than Arctic amplification. To avoid restrictive interpretations, we thus decided not to mention Arctic amplification as a possible explanation.

Minor comments

p. 1, l. 24: suggest: "have extended well outside their current margins".

Thank you. Done.

p. 2, l. 22: could you add a reference and a timing for LGM?

Done.

p. 3, l. 1: suggest to replace “thus” with “still”.

Done.

p. 3, l. 3: add s to responses.

Done.

p. 3, l. 18: something missing in the sentence, suggest “formulation” after “creep”.

Done.

p. 4, l. 4: suggest to replace “field” with “sheet”.

Done.

p. 5, Fig. 1: c) can you add a scale and maybe indication with a box in b) where this extract is from? “from the estimate” (not plural in line 4 of caption), Line 6 (PDD) is not acronym for surface mass balance, some more explanation is needed here, indicate also, like in the other figures that h) is January and i) is July figures.

We have added a scale, marked the inset location, and clarified the text.

p. 6, l. 6: suggest to replace “of” with “with”.

Done.

p. 6, l. 14: suggest “The climate forcing driving the ice sheet simulations consist spatially of a present-day monthly mean climatology...“

Done.

p. 6, l. 15: suggest to delete “s” on corrections.

Done.

p. 6, l. 19: add “mean” after monthly.

Done.

p. 6, l. 22: note, if true (clarify in Figure caption, see comment above) then the reference should be to Fig. 1 i) for summer precipitation.

This is true, done.

p. 6, l. 27: replace “is” with “are”.

Done.

p. 6, footnote: add a reference for the correct formula for the rigidity and clarify (add something like, the consequence of this error is that the simulations effectively use....) Delete “in” before “a small” and add a quantification of the small change in the length scale – how small, is it a few percentage?

The correct formula can be found in the study by Love (1906, p. 443). The lenght scale of bedrock deformation can be computed as $\alpha = \sqrt[4]{\frac{4D}{(\rho_m - \rho_l)g}}$ (Walcott, 1970), thus the error in lenght scale can be expressed as $\sqrt[4]{1+\nu} - 1 = 5.7\%$. The footnote was clarified and references were added.

p. 7, l. 2: “shipped with WorldClim” is not clear, please edit, also suggest not to use b for topography, s surf and s bed , or h would be better.

We clarified the sentence. However, we would like to keep the current notation to remain consistent with previous papers (Seguinot, 2014; Seguinot et al., 2014).

p. 7, l. 19: add “the” before “oxygen”.

Done.

p. 7, l. 24: “and within a rectangular region ..” is not clear, edit this text.

The sentence was reorganised.

p. 8: add “acceleration of” before gravity, add a reference for the ideal gas constant?

Done.

p. 9, l. 14–15: see comment above, could this be an example of Arctic amplification?

Please refer to my comment above.

p. 9, l. 19: add “a” before “very” and suggest to turn the sentence around, the EPICA simulations are in a good agreement with the data.

Done.

p. 9, l. 20: followed by first a retreat and then a standstill? replace “blue” with “red”.

Done.

p. 9, l. 21: suggest : The simulations forced by the GRIP palaeo-temperature forcing yield ... (blue curves)”.

Done.

p. 10, l. 2: suggest to add “followed by a rapid retreat”.

Done.

p. 10, l. 3: why state “two or three” in intro the suggestion is either 4 major or 15, is there a reference for 2 or 3?

The numbers 4 and 15 relate to the total (minimum) number of Pleistocene glaciations. However, evidence for pre-LGM glaciations during the last glacial cycle is debated and very limited (see later part of the introduction). We added the word “Pleistocene” in the introduction and clarified the concerned sentence about model results.

p. 10, l. 10: suggest to replace “lower” with “smaller”.

Done.

p. 10, l. 11: is this due to Arctic Amplification?

Please refer to my comment above.

p. 10, l. 12: suggest to replace “least” with “the smallest”.

Done.

p. 11, Fig. 3 caption: what does “cumulative” mean here? Do you mean maximum in each location? clarify what the black line indicates. No solid red line is visible in figures. What is meant with “reasonable”, maybe replace with “realistic”? suggest to replace “cover” with “extent”.

We replaced “cumulative extent of modelled ice cover” with “modelled maximum extent”, “reasonable” with “realistic”, and “red line” with “black line”, which is what we meant.

p. 11, l. 2: suggest to replace “cumulative” with “maximum extent in each area” or something similar.

As for the caption, we replaced with “modelled maximum extent”.

p. 11, l. 1–3: how sensitive is the model to different parameters in the applied sliding formulation?

Please refer to my comment above.

p. 11, l. 4–5: “outside this benchmark” clarify if you mean spatially or temporally.

Done. We mean spatially.

p. 11, l. 6–11: is this text better fitted in a discussion section?

We have included this discussion here as we think that understanding the simiarities and differences in the spatial patterns of glaciation between the different palaeotemperature records used is necessary to justifying the choice of the EPICA forcing used in the next section. We think that this non-standard outline is the best way to present all results in a single manuscript.

p. 12, l. 2: suggest to replace “higher” with “larger”.

Done.

p. 12, l. 4: do you mean to refer to Fig. 3?

No, but the reference to Fig. 2 was misplaced. This has been corrected.

p. 12, l. 29–32: does this text fit better in method section?

We agree that this text does not really fit in a results and discussion section. However, this information is specific to Sect. 4. We feel that moving these and the corresponding sentences in Sect. 3 to the methods section would increase the complexity of the manuscript.

p. 13, Fig. 4 caption: the 200 m surface contours are not clearly visible in the figure, can they be made sharper, or just skipped? Line 3, something like "are shown" is missing. Suggest to replace"background" with "bedrock". This is the first time "Natural Earth Data" is mentioned, should that be in the section on the data? Suggest to replace "Gray fields" with "shaded gray area" and "boundaries" with "timing".

The 200 m contours were thickened, the caption was reworked as suggested, and the reference to Natural Earth Data was moved to the caption of Fig. 1.

p. 15, l. 8: replace "was" with "is".

Done.

p. 15, l. 25: "occurred".

Done.

p. 16, Fig. 5: in figure the color bar is written to indicated maximum surface elevation, but in figure caption the maximum ice thickness, which is correct? The surface elevation contours are not clearly visible. The dark orange color in the figure, that covers the central part of the ice sheet is not (?) in the bar on the left (or is it before 27 ka BP?).

The map shows maximum thickness. The colourbar label was corrected. Surface elevation contours were thickened. Indeed, in much of the mountain area maximum thickness is reached before 27 ka. This is now clarified in the figure caption.

p. 17, l. 30: suggest to replace “have” with “could”.

Done.

p. 18, Fig. 6: the 200 m contours are not clearly visible.

The 200 m contours were thickened.

p. 19, l. 7: could you add what the modelled regional ice thickness is, for comparison?

Done.

p. 20, Fig. 7: add info about the gray areas indicating MIS 4 and 2 “Isolated patches indicate periodic surges from tributary glaciers” needs more explanation and it is not clear what is meant. Does the model simulate periodic surges?

We added the info about MIS. The wording “periodic surges” was badly chosen and replaced by a more cautious “episodic advances”. These advances are likely due to thermodynamical feedbacks modulated by fluctuations in the climate forcing, but they were not explored in detail and perhaps depend on model resolution.

p. 21, l. 21: here is a reference for 2 or 3 glaciations (see comment above) but in the intro is only mentioned 4 or 15, suggest to change text to harmonize.

See my previous comment about last glacial cycle and older glaciations.

p. 21, l. 27: suggest to edit “the study consists of” or start for example like “In this study the model has been applied...”

Done.

p. 21, l. 28: how important is it that the model has been validated for the Cordilleran ice sheet? Will that support the choices of the sliding model applied in the Alps? I think that it would be valuable for this study to do a sensitivity runs for at least some of the model parameter choices.

The reference to the Cordilleran ice sheet was removed here. As mentioned in the later part of the conclusions, it is clear to us that additional sensitivity studies are needed. With this study, we hope to have highlighted areas of research were data-model comparison could be pursued further. However, this will require not only more model runs, but also a more systematic classication of geological data in digital databases.

p. 22, l. 6: add "records" after forcing.

We replaced "forcing" by "records".

p. 22, l. 19: why do you add "potentially" here? Isn't this a firm conclusion from you study?

The timing of the LGM extent depends on the actual climate history of the European Alps, which was almost certainly different and more complex than our climate forcing scenarii. Although our simulations show that even a spatially homogeneous forcing produces spatial variations in the timing of maximum extent, on can not exclude that a different climate history might counteract these variations.

p. 22, l. 20: suggest to replace "higher" with "larger".

Done.

p. 22, l. 22: same as above, why "potentially" here?

We removed the first "potentially". Nevertheless, the actual number and timing of

glacier advances onto the foreland depends on Alpine climate history, which may have been very different from the forcing used in our simulations.

p. 22, l. 24: suggest to replace “nevertheless” with “however” or edit the sentence.

Done.

p. 22, l. 26–28: the paper would be able to give stronger conclusions with sensitivity study, suggest to edit the sentence by replace “statements” with “limitations” or “drawbacks” and “last glacier cycle ice dynamics in the Alps” is not easy to read.

Done. The complicated sentence was rephrased.

p. 23, l. 2: replace “mode” with “more”.

Done.

Figures are generally clear and well set up. The surface contours in Figs 4,5 and 6 is not clearly visible in my printout and could maybe become clearer?

Thank you. The 200 m contour levels were thickened on all figures. We thank you again very much for the time and effort you put into this very meticulous review.

References

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