Review of *"Testing the consistency between changes in simulated climate and Alpine glacier length over the past millennium"* by Goosse et al.

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In this manuscript, Goosse and co-authors examine the possibility of using modelled glacier length changes to investigate modelled past climatic conditions. To model past glacier changes, they use a newly developed state-of-the-art glacier model (OGGM) (Maussion et al., 2018), while for the climatic aspect of the work they rely on variables derived from the PMIP3 and the CMIP5 protocols. A total of 71 glaciers in the European Alps are modelled throughout the previous millennium, and from this it is clear that the modelled length fluctuations are far more sensitive to differences in modelled climate (which is used as an input to drive OGGM), than to the OGGM model parameters. This suggests that modelled glacier length changes can be used as an interesting alternative/complimentary approach to other widely used palaeo-archives (e.g. trees, pollen,...) that are typically used to evaluate model performance.

I greatly enjoyed reading this manuscript. The results are generally well presented and the text is compact, well written and clear. Although not being an expert in past climate variability, I was able to follow the main points and the conclusions drawn from this. Some passages in the text were not entirely clear to me, and sometimes a few additional references would be welcome. I think that with a bit of reworking, this manuscript will be of great value to this journal and its readership. My list of comments may seem long in first instance, but most are suggestions that should be easily implemented.

General comments

- Some of the glaciological aspects of the manuscript were only very shortly treated, and in some cases a bit more explanation / additional framing would be welcome. I understand that most of the OGGM model description is summarized in Maussion et al. (2018), but it would be nice if the manuscript could be read without having to refer to the other one. My (sometimes rather specific) comments on this are detailed below.
- Not all figures were straightforward to interpret and for some of them I had to look several times before I got the main message. A few suggestions on how to possibly improve these figures are formulated at the end of this review.

Specific and technical comments

1. Introduction

- p.2, l.12-14: the emphasize is on the fact that glacier changes are mainly driven by changes in summer temperatures and winter precipitation. But what about insolation changes and other changes related to incoming radiation (e.g. aerosols, volcanism,..)? Aren't these important, especially on longer time scales and before the industrial revolution, when the strong anthropogenic atmospheric temperature signal was not yet present. It would be good if a few words would be spent on this. Furthermore, the effect of precipitation is in fact barely described throughout the manuscript and the focus is almost solely on (summer) temperatures. Some other authors pone that winter precipitation is very important and may for instance have been one of the main mechanisms behind the 1800-1850 glacier advance (e.g. Vincent et al., 2005).

- p.2, l.14-15: ”Furthermore, glaciers integrate forcing over timescales ranging ranging from a few years to several decades or even centuries”. This is correct, and is related to their response time. I would suggest to explicitly state this here, as this may not be clear to a non-glaciologist, and add some references to some of the classic works on this (e.g. Jóhannesson et al., 1989; Leysinger Vieli and Gudmundsson, 2004). It would also be in better harmony with your next sentence, in which you describe other records as having ”a much faster response”.

- p.2, l.17: would also refer to a recent study of Roe et al. (2017) here, in which glacier retreat is described as an evidence for changing climatic conditions, and in which it is also explained that these changes can not directly be compared to changes in climatic conditions and related proxies (which they circumvent by utilizing a signal-to-noise analysis).

- p.2 l.19-21: many references, but only to recent studies, which gives the impression that this is a recent study field. This is in fact not the case, as simple glacier models have been used since a long time to better understand past climatic conditions. Here a reference to some pioneering studies, such as for instance to Allison and Kruss (1977) and Oerlemans (1986) would be justified. Notice that these older studies used simplified ice flow models that are in fact very similar to the flow model used in the OGGM model. The main difference resides of course in the fact that OGGM can be applied at a much larger scale (cf. 'Global' in its nomenclature), while in the earlier studies typically only one glacier was modelled to better understand past conditions. The authors could also decide on mentioning this in the text. Furthermore a reference could also be added to the recent study by Doughty et al. (2017).

- p.2, l.27-29: cf. earlier comment. What about insolation changes?

- p.3, l.7-9: from the sentence and the references, it looks like Farinotti et al. (2017) is also a glacier modelling study. This is not the case, as this study treats ice thickness / bedrock elevation modelling, which is in its turn an important input of glacier models. I would suggest removing the reference to Farinotti et al. (2017) here and instead mention it later: ”...to the glacier model rather than to the climate model” → ”...to the glacier model and its input/boundary conditions (e.g. the ice thickness (Farinotti et al., 2017)) rather than to the climate model”.

- p.3, l.10-13: when reading this, I found it to be a bit strangely placed here and obstructing the flow of the introduction with little added value. Consider omitting or moving this to the discussion section?

- p.3, l.17-18: did not understand this sentence in first instance, as I was confused with the 'modelled as well as reconstructed temperature changes'. It only became clear to me what this meant when I read section 3 and got that first the temperatures (modelled and reconstructed) are compared and subsequently they are linked to the glacier fluctuations. Maybe slightly reformulate this sentence to make this point clearer.

- p.3, l.21-22. Maybe strange that I suggest this, as the authors of this particular study are co-authors on the study presented here, but think it would also be nice to refer to the very recent study by Marzeion et al. (2018).

- p.3, l.23-24: initial focus is on the European Alps, because here the records are long enough for analysis. To my knowledge, there are also several glaciers in Scandinavia with a very long record (e.g. Leclercq et al., 2014). Why where these glaciers not used/excluded? It seems that all necessary data available needed for this study (i.e. data that was used for European glaciers) would also be available for those glaciers.

2.1 Climate model results

- p.4, l.4-5: reference to (Otto-Bliesner et al., 2009). This is a reference to a workshop, related to PMIP2 (vs. PMIP3 in text). Any better/newer reference available?

2.2 The Open Global Glacier Model

- There is one main, rather crucial part in the model, that I am missing in this section. This relates to modelling/calculations for the regions that are not ice covered today. I understand that it is not the goal here to go into too many details regarding OGGM, but I think this part should be elaborated. It is very difficult to model the dynamics/evolution of the prefrontal areas that are not ice covered today with a simple ice flow model as several issues arise: e.g. how will the shape of the transects look? In which direction/where does the ice flow? And this part is rather crucial in this study, as most of the changes modelled here occur in this pre-frontal area (compared to the present-day period). For studies focusing on the future evolution of glaciers, this is less important, as they are assumed to shrink in the future and the 'action' occurs in regions where the treatment of for instance the cross sectional shape is more straightforward. As the authors (nicely!) show later, the choice of OGGM model parameters is not crucial for their modelled evolution over the past millennium, but despite this I think it would still be important that the 'prefrontal action/modelling' is explained in more detail here.

- p.4, l.18-19. RGI version 5. Is the latest version of the RGI (RGI 6) not automatically used in OGGM? Not a big deal anyway, since the outlines did not change for Europe between these two versions (I think).
- p.4, l.30: melting occurs if the monthly temperature is above -1C. Why was this limit chosen? It would not seem unreasonable to have some melting also in months with a lower mean monthly temperature. If based on a study/observations, would be good if could be mentioned.
- p.5, l.3: 'based on the shallow-ice approximation'. Is evident was this is for glaciologists (for modellers at least), but here the main public are not glaciologist (or not only limited to them). Would be good if you could explain the shallow-ice approximation in a sentence (horizontal scale much larger than vertical scales considered, ice flow depends on local geometry,..etc.) and add a reference to Hutter (1983).
- p.5, l.5-7: strangely formulated. Here you say that the rate factor mainly changes as a function of ice temperature (which is true!). But in fact all glaciers in the European Alps are (very close to) their melting point, i.e. they are temperate glacier. So by reading this, it does not really make sense that there would be a wide spread in the values of the rate factor. However, due to impurities, ice fabrics, crystal orientation,...etc, the values for the rate factor vary by quite a lot, even for the glaciers in the European Alps (I come back to this point in my comments on section 4). Would be good if you can reformulate this passage.
- Basal sliding is not treated/neglected it seems. This is an acceptable approach, and has been used in several studies for Alpine glaciers (e.g. Gudmundsson, 1999), as ice motion due to internal deformation and basal sliding is typically occurring in the same places (e.g. Zekollari et al., 2013). This treatment of basal sliding should briefly be mentioned somewhere.

2.3 Glacier length observations

- p.5, l.23-25: for the historical sources, (old topographical) maps should also be named, as they are widely used to document past changes. Would suggest adding a reference to Purdie et al. (2014) also. Could also update (Nussbaumer and Zumbühl, 2012) to a more recent work of these authors: Zumbühl and Nussbaumer (2018).
- p.5, l.27: Leroy et al. (2015) → Le Roy et al. (2015).
- p.5, l.28-30: see my earlier comment regarding glaciers in Scandinavia with a long length record and the question why these are not considered here.

3. Simulated and reconstructed glacier changes

This section starts by comparing the modelled temperatures with observations. Subsequently the observed and modelled length variations are explained. The observed ("reconstructed") changes were already described earlier, and therefore I found the title of this subsection not entirely logical. Also taking into account that first temperatures are described, it would be more logical to name this subsection 'Simulated temperatures and glacier changes' or 'Simulated versus reconstructed glacier changes'. I found this elaborate section well written and liked the short paragraphs and summarizing sentences at the end of various parts (e.g. p.7, l.22-24), which made it easy to follow.

- p.7, l.7: "trend" → "growth trend"?
- p.7, l.14-24: would merge these two paragraphs, as the second one is a continuation of the first one.
- p.7, l.34: "have a large positive trend": of what? Temperature trend?

- p.8, l.28: ”between Alpine regions or glaciers”: found this a bit vague. Maybe just change to ”between regions” (clear that is in Alps), or simply drop this part of the sentence.
- p.8, l.28: Leroy et al. (2015) → Le Roy et al. (2015).
- p.8, l.33-34: sentence not entirely clear. Consider reformulating
- p.9, l.1-2: ”have a long response timescales” → ”have long response timescales”

4. Sensitivity of glacier changes to model parameters

- p.9, l.22-23: the rate factor is doubled as a sensitivity experiment. Why is there no experiment with a lower rate factor (e.g. halving)? In various (flowline) modelling studies in which the rate factor was calibrated (e.g. to reproduce observed surface velocities), lower values than the 2.4E-24 adopted here were obtained. Three studies that have for instance found/adopted a (much) lower rate factor:
  - 2E-24 $Pa^{-3}a^{-1}$ (Le Meur et al., 2004)
  - 6E-25 $Pa^{-3}a^{-1}$ (Stroeven et al., 1989)
  - 6E-25 $Pa^{-3}a^{-1}$ (Letréguilly and Reynaud, 1989)
- p.10, l.9: ”similar results have been obtained for other ones” → ”similar results have been obtained for other climate models”?
- p.10, l.9-10: ”The results for CESM ensemble” → ”The results for the CESM ensemble”

5. Conclusions

- p.10 last lines - p.11, first lines. Discussion about the end of the LIA and the potential role of black carbon and how a recent study by Sigl et al. (2018) shows that this is unlikely. Lüthi (2014) also showed that the role of black carbon is most likely very limited to non-existent to explain the observed retreat. Also mention this here?
- p.11, l.6-11. Not entirely sure whether your results 100% support this statement. Some simulations based on a particular climate model may result in a correct retreat, but this may in some cases be related to other reasons. By this, I hint in the direction of the role of other important variables for the glacier SMB, such as the winter precipitation and the insolation, which are not really elaborately treated/described in your work. Would be nice if this could be slightly reframed.
- p.11, l.15-16: could you maybe mention how this relates to other regions? (cf. work of Solomina et al., 2015, 2016) i.e. how does in other regions the present-day length compare to minimum glacier lengths over the past 1000 years?
- p.11, l.18: ”simulated and observed values”. What does ”values” refer to here? Climate or glacier length?
- p.11, l.19-21: How can a strong retreat be modelled for this period if there is no real temperature signal? Your story is build up around the dominant effect of (summer) temperatures on glacier MB (and thus length fluctuations). How come then that you model a glacier retreat for this period? Is this related to their response time (i.e. reacting to an earlier T signal) or is there a signal in the precipitation for instance? You make it sounds as if the cause-effect mechanism is unclear, but as you model this, it should be feasible to find this out, no?
- p.11, last sentence: consider adding ”...of past climate reconstructions”

Figures

- Fig.1, 2, 3, 5 & 6: found it very difficult to distinct between CESM and CCSM4, as the lines have almost the same colour. Would be nice if more distinct colours could be used.

- Fig.1: nice to have the reconstruction a bit thicker, so that it can be distinguished in a relatively easy manner from the modelled ones. It would be nice if you could also do this (i.e. bolder line for the 'Observation') for the length reconstructions (Fig. 2, 3, 5, 7). Especially in Fig.5, it is difficult to distinct the observed form the modelled values in an intuitive way.
- Fig.2, caption: "The reference period is 1901-1930": drop "the years" (cf. caption Fig. 3)
- Fig.4a,b: had to look several times at the figure before I got it. Find it a bit strange that you present the observation as the last 'column' in each figure, in the same style as the modelled values. As it is a single value, it would be nice if the observations could shown as a dotted horizontal line that crosses the entire box. This would make the figure easier to interpret.
- Fig.6: a comment in the same line as the previous one: it is difficult to detect what the observation is. Given its different nature (observed vs. modelled), a different symbol for the observation, e.g. larger, with different face and edge colour for instance, would be adequate here.

References

Allison, I. and Kruss, P.: Estimation of Recent Climate Change in Irian Jaya by Numerical Modeling of Its Tropical Glaciers, Arctic and Alpine Research, 9, 49–60, 1977.

Doughty, A. M., Mackintosh, A. N., Anderson, B. M., Dadic, R., Putnam, A. E., Barrell, D. J. A., et al.: An exercise in glacier length modeling: Interannual climatic variability alone cannot explain Holocene glacier fluctuations in New Zealand, Earth and Planetary Science Letters, 470, 48–53, doi:10.1016/j.epsl.2017.04.032, 2017.

Farinotti, D., Brinkerhoff, D. J., Clarke, G. K., Fürst, J. J., Frey, H., Gantayat, P., et al.: How accurate are estimates of glacier ice thickness? Results from ITMIX, the Ice Thickness Models Intercomparison eXperiment, The Cryosphere, 11, 949–970, doi:10.5194/tc-11-949-2017, 2017.

Gudmundsson, G. H.: A three-dimensional numerical model of the confluence area of Unteraargletscher, Bernese Alps, Switzerland, Journal of Glaciology, 45, 219–230, doi:10.3189/002214399793377086, 1999.

Hutter, K.: Theoretical Glaciology, Reidel Publ. Co., Dordrecht, 1983.

Jóhannesson, T., Raymond, C. F., and Waddington, E. D.: A simple method for determining the response time of glaciers, in: Glacier Fluctuations and Climatic Change, pp. 343–352, Kluwer Academic Publishers, 1989.

Le Meur, E., Gagliardini, O., Zwinger, T., and Ruokolainen, J.: Glacier flow modelling: A comparison of the Shallow Ice Approximation and the full-Stokes solution, Comptes Rendus Physique, 5, 709–722, doi:10.1016/j.crhy.2004.10.001, 2004.

Le Roy, M., Nicolussi, K., Deline, P., Astrade, L., Edouard, J. L., Miramont, C., et al.: Calendar-dated glacier variations in the western European Alps during the Neoglacial: The Mer de Glace record, Mont Blanc massif, Quaternary Science Reviews, 108, 1–22, doi:10.1016/j.quascirev.2014.10.033, 2015.

Leclercq, P. W., Oerlemans, J., Basagic, H. J., Bushueva, I., Cook, A. J., and Le Bris, R.: A data set of worldwide glacier length fluctuations, The Cryosphere, 8, 659–672, doi:10.5194/tc-8-659-2014, 2014.

Letréguilly, A. and Reynaud, L.: Past and forecast fluctuations of Glacier Blanc (French Alps), Annals of Glaciology, 13, 159–163, 1989.

Leysinger Vieli, G. J.-M. C. and Gudmundsson, G. H.: On estimating length fluctuations of glaciers caused by changes in climatic forcing, Journal of Geophysical Research, 109, F01 007, doi:10.1029/2003JF000027, 2004.

Lüthi, M. P.: Little Ice Age climate reconstruction from ensemble reanalysis of Alpine glacier fluctuations, The Cryosphere, 8, 639–650, doi:10.5194/tc-8-639-2014, 2014.

Marzeion, B., Kaser, G., Maussion, F., and Champollion, N.: Limited influence of climate change mitigation on short-term glacier mass loss, Nature Climate Change, 8, 305–308, doi:10.1038/s41558-018-0093-1, 2018.

Maussion, F., Butenko, A., Eis, J., Fourteau, K., Jarosch, A. H., Landmann, J., et al.: The Open Global Glacier Model (OGGM) v1.0, Geoscientific Model Development Discussions, pp. 1–33, doi:10.5194/gmd-2018-9, 2018.

Nussbaumer, S. U. and Zumbühl, H. J.: The Little Ice Age history of the Glacier des Bossons (Mont Blanc massif, France): A new high-resolution glacier length curve based on historical documents, Climatic Change, 111, 301–334, doi:10.1007/s10584-011-0130-9, 2012.

Oerlemans, J.: Glaciers as indicators of a carbon dioxide warming, Nature, 320, 607–609, doi:10.1038/320607a0, 1986.

Otto-Bliesner, B. L., Joussaume, S., Braconnot, P., Harrison, S. P., and Abe-Ouchi, A.: Modeling and Data Syntheses of Past Climates: Paleoclimate Modelling Intercomparison Project Phase II Workshop; Estes Park, Colorado, 15–19 September 2008, Eos, Transactions American Geophysical Union, 90, 93, 2009.

Purdie, H., Anderson, B., Chinn, T., Owens, I., Mackintosh, A., and Lawson, W.: Franz Josef and Fox Glaciers, New Zealand: Historic length records, Global and Planetary Change, 121, 41–52, doi:10.1016/j.gloplacha.2014.06.008, 2014.

Roe, G. H., Baker, M. B., and Herla, F.: Centennial glacier retreat as categorical evidence of regional climate change, Nature Geoscience, 10, 95–99, doi:10.1038/ngeo2863, 2017.

Sigl, M., Abram, N. J., Gabrieli, J., Jenk, T. M., and Osmont, D.: No role for industrial black carbon in forcing 19 th century glacier retreat in the Alps, The Cryosphere Discussions, doi:10.5194/tc-2018-22, 2018.

Solomina, O. N., Bradley, R. S., Hodgson, D. A., Ivy-Ochs, S., Jomelli, V., Mackintosh, A. N., et al.: Holocene glacier fluctuations, Quaternary Science Reviews, 111, 9–34, doi:10.1016/j.quascirev.2014.11.018, 2015.

Solomina, O. N., Bradley, R. S., Jomelli, V., Geirsdottir, A., Kaufman, D. S., Koch, J., et al.: Glacier fluctuations during the past 2000 years, Quaternary Science Reviews, 149, 61–90, doi:10.1016/j.quascirev.2016.04.008, 2016.

Stroeven, A., van de Wal, R., and Oerlemans, J.: Historic front variations of the Rhone Glacier: simulation with an ice flow model, in: Glacier Fluctuations and Climate Change, edited by Oerlemans, J., pp. 391–405, Kluwer Academic Publishers, 1989.

Vincent, C., Le Meur, E., Six, D., and Funk, M.: Solving the paradox of the end of the Little Ice Age in the Alps, Geophysical Research Letters, 32, 1–4, doi:10.1029/2005GL022552, 2005.

Zekollari, H., Huybrechts, P., Fürst, J. J., Rybak, O., and Eisen, O.: Calibration of a higher-order 3-D ice-flow model of the Morteratsch glacier complex, Engadin, Switzerland, Annals of Glaciology, 54, 343–351, doi:10.3189/2013AoG63A434, 2013.

Zumbühl, H. J. and Nussbaumer, S.: Little ice age glacier history of the central and western Alps from pictorial documents, Cuadernos de Investigación Geográfica, 44, 115–136, doi:doi.org/10.18172/cig.3363, 2018.