Dear Editor,

We would like to thank you again for the evaluation of our manuscript and your suggestions.

We have implemented in the revised version submitted today the modifications proposed in our answer to the Referees as well as your editorial comments.

For editorial comments specifically,

We confirm that the climate model results are stored on a permanent archive.

We have explained in the revised version the CMIP/PMIP terminology and the definition of the ‘past1000’ experiments;

We mention explicitly in the revised that the behavior seen on Figure 2 for some glaciers is similar to the ones of many others (supplementary Figure 1) and the Figure 2 provides just an illustration for five well-known glaciers.

We have added the meaning of the bar for CESM in the caption of Figure 4.

We have also corrected the grammatical errors and the typos.

The results of our simulations will also be stored a permanent archive. The address will be provided for the final version (the transfer is under way).

Best regards

Hugues Goosse

Response to Referee 1

Comments of the Referee:

The overall quality of the paper is good and this manuscript addresses scientific questions that is relevant and within the scope of CP and the paper presents novel concepts, ideas, tools, and data. The scientific methods and assumptions are valid and clearly outlined in the manuscript. The results are sufficient to support the interpretations and conclusions and the conclusions are valid based on the data and model results.

The description of the data and model experiments is sufficiently complete and precise to allow their reproduction by other researchers. The authors give proper credit and references to related work and clearly indicate their own contribution.

The title, as well as the abstract, clearly reflects the contents of the paper and the abstract provides a concise and complete summary of the paper. The manuscript is well structured and the English language is apparently fluent and precise. The mathematical formula on page 4, symbols, abbreviations, and units are correctly defined and used.

Finally, I do not see that any parts of the paper, including text, formula, figures, and tables, need to be clarified, reduced, combined, or eliminated. In addition, the references seem relevant and the amount and quality of supplementary material is appropriate.

Answer of the authors :

We would like to thank the Referee for their time and the positive evaluation of our work.

Response to reviewer 2

The Referee's comments below are in italics, our answer in plain font

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.

We would like to thank the Referee for their very careful evaluation and for the suggestions that will greatly help us to improve the quality of our manuscript.

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.*

We will expand in the revised version the description of the glaciological aspects of the manuscript, as suggested. The proposed modifications will be described below in the answers to the specific comments.

• *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.*

We will modify the figures following the suggestions of the Referee in order to make their interpretation more straightforward.

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).*

This sentence in the introduction is very general and we do not expect to go into the details at this stage but we will include in the revised manuscript the potential impact of incoming radiation.

The potential role of precipitation will be expanded at the beginning of section 3.

'Enhanced winter precipitation has been suggested to be an important contributor to some past changes in glacier length in the Alps (e.g., Vincent et al., 2005; Steiner et al. 2005; Steiner et al. 2008). Nevertheless, summer temperature is generally considered as the major driver of European glacier fluctuations at centennial timescales (Oerlemans, 2001; Steiner et al. 2005; Huss et al., 2008; Steiner et al., 2008; Leclerq and Oerlemans, 2012; Zekollari et al., 2014). It is thus instructive to compare first the simulated temperatures with reconstructions before analysing the glacier themselves.'

Additionally, we have repeated the equivalent of Figure 6 for winter precipitation (Figure R1). The link with glacier length changes is much weaker than for summer temperature. It is also less straightforward to interpret. Temperature and precipitation trends are positively correlated in some experiments, with a potential influence on the correlation between glacier length changes and precipitation. This might explain why, for instance, larger precipitation rates are generally associated with a retreat of the glaciers on the panel b of Figure R1. It is also possible that models underestimate the contribution of precipitation changes on glacier length because of a too low decadal variability of precipitation over the Alps, as suggested for some other regions (e.g., PAGES Hydro2k Consortium, 2017; Seftigen et al. 2017), and because of their coarse resolution that limits their ability to reproduce adequately precipitation changes in mountainous areas. Nevertheless, investigating those processes is out of the scope of the present study. Consequently, we have chosen to not include this additional figure in the manuscript.

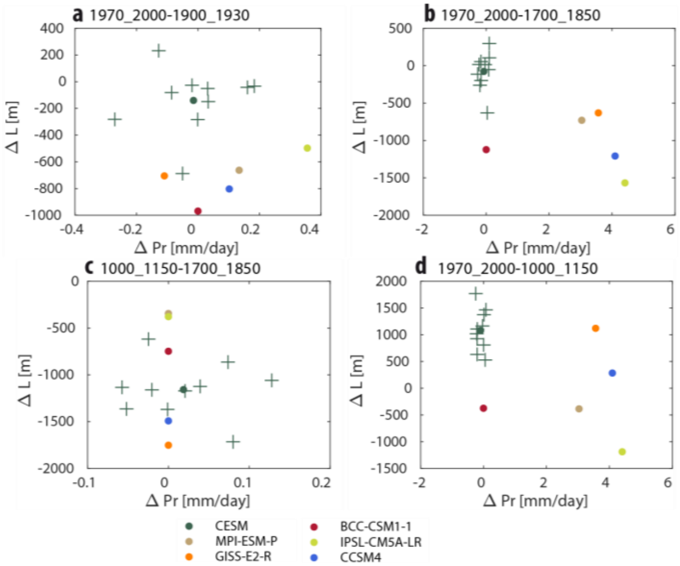

Figure R1. Glacier length changes as a function of winter precipitation (DJF) changes for the differences between a) 1970-2000 and 1900-1930; b) 1970-2000 and 1700-1850; c) 1000-1150 and 1700-1850; d) 1970-2000 and 1000-1150. The crosses represent the individual CESM ensemble members, the ensemble mean being represented by a dot of the same color.

p.2, l.14-15: "Furthermore, glaciers integrate forcing over timescales 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. Johannesson 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".

As suggested, we will add 'because of their long response time' and the references in the revised version.

• 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).

The reference will be added in the revised version.

• 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).

The suggested references will be added.

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

Temperature and precipitation provide just an example. This will be specified in the revised version.

- *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".*

The reference will be moved in the revised version, as suggested.

- *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?*

Internal variability is potentially an important cause of disagreement between simulated and observed glacier length. We consider that it is necessary to cite the key references in the introduction but the last sentence of the paragraph will be suppressed in the revised version to facilitate the flow.

- *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.*

This sentence will be reformulated in the revised version. As testing the compatibility between simulated and reconstructed temperatures is not the main goal of our study, this part of the sentence will be suppressed to avoid confusion.

- *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).*

The reference will be added.

- *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.*

There are 14 Scandinavian glaciers in the compilation of Leclercq et al. (2014) that meets our criteria (data covering at least the 20th century). Some of those glaciers are strongly influenced by the inflow of marine air, while some others have a more continental climate. This means that the number of samples that corresponds to similar climatic conditions is relatively limited. Consequently, biases in simulated length for one or two specific glaciers, which are expected for a model like OGGM, could have a large impact on the average. With 71 glaciers in relatively similar climatic conditions, the sensitivity of the average to biases in a few glaciers is much smaller in the Alps. We thus expect our results to be more robust in this area. This is the reason why we have chosen to focus on the Alps first. In the near future, we expect to repeat our analysis globally to check how the conclusions differ for different areas.

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?*

In the revised version, we will cite for PMIP3 the specific paper describing the forcing that has to be applied for the past millennium and a general paper analyzing PMIP3 simulation results.

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.*

A central information needed in OGGM to compute the flow is the shape of the glacier bed and the slope along the flowline, which can be computed for areas that are not ice covered today (with actually less uncertainties than for some of the glaciated areas), so we expect the glacier forefront to be well simulated. Specifically, as explained in Maussion et al. (2018), for the prefrontal areas, we compute the direction and path of ice flow by computing the route from the glacier tongue toward the end of the domain that is the least costly in terms of positive altitudinal change. The flowline therefore follows the valley as a river would do. Along this flowline, we estimate the shape of the bed by fitting a parabola to the intersection points between the actual topography and the normal to the flowline.

A brief description of those processes will be included in the revised version.

- *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).*

We made the first simulations with RGI version 5, which was the latest version available at that time, and did not update the data set as we checked that there are no differences for the selected European glaciers, as suggested by the reviewer.

- *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.*

This temperature was chosen on the result of a cross-validation procedure similar to the one conducted by Marzeion et al. (2012). The model is not very sensitive to the choice of this value as the calibration procedure of the mass-balance model is very robust and efficient in compensating for unrealistic temperatures as well as approximations inherent to the simple temperature index model (Maussion et al. 2018).
The way this value is obtained will be included in the revised version.

• 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).

As suggested by the reviewer, a brief description of the shallow-ice approximation will be added in the revised version "In the shallow ice approximation, the vertical variations of ice flow are neglected and only a depth-integrated ice velocity is computed. This is a common approximation for computationally efficient ice flow models, and it is largely valid as long as the considered horizontal scales are much larger than the vertical scales. (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.

We agree with the reviewer that the sentence may be confusing as it mixes information on the processes that may affect A in the real world, at global scale, and the origin of the uncertainty of A in OGGM when applied to the Alps. As our goal is not to get into the details here, we propose to simplify the sentence and mention 'while in reality A may change by a factor 10 between glaciers due to a wide range of processes (Cuffey and Paterson, 2010) '.

• 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.

Basal sliding can be included in OGGM but it is not activated in our simulations. This will be specified in the revised version.

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).

As suggested, we will add in the revised version the old maps as an example of historical source and will cite the suggested references.

• p.5, l.27: Leroy et al. (2015) ! Le Roy et al. (2015).

Thanks. This will be corrected.

• 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.

As discussed above, we have preferred to focus this first study on the European Alps only.

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.

As suggested, we will modify the title. As the focus is on the glacier, not on temperature, we propose to use 'Simulated glacier changes'.

- *p.7, l.7: "trend" ! "growth trend"?*

We will modify the text as suggested.

- *p.7, l.14-24: would merge these two paragraphs, as the second one is a continuation of the first one.*

The two paragraphs will be merged in the revised version.

- *p.7, l.34: "have a large positive trend": of what? Temperature trend?*

It is a trend in the length of the glacier. This will be specified in the revised version by using 'growth 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.*

In the revised version, we will use 'between regions' because it is indeed clear that it is in the Alps.

- *p.8, l.28: Leroy et al. (2015) ! Le Roy et al. (2015).*

This will be corrected, thanks.

- *p.8, l.33-34: sentence not entirely clear. Consider reformulating*

The whole paragraph will be reformulated: 'The early 15th century corresponds to a minimum for glacier advances in many models (Fig. 5) and a relative minimum in glacier length (Fig. 3). Although the simulated temperatures are generally mild during this period, they are not high and, in particular, are generally lower than in the beginning of the millennium (Fig. 1). This clearly illustrates the impact of the long response timescales of glaciers. The simulated glacier retreats in the early 15th century appears as partly due to the temperatures at that time but also to the recovery from the large advances in the 13th and 14th century.'

- *p.9, l.1-2: "have a long response timescales" ! "have long response timescales"*

We will modify the text as suggested.

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)*

As suggested, we have made an additional experiment with a creep factor divided by two. The difference with the standard solution are also small, not modifying our conclusions. This additional experiment will be included in the revised version. Additionally, to save space, we will only show in the revised version the results for CCSM4 as we consider that the results for one model only are sufficient to illustrate the weak sensitivity of the results to OGGM parameters (the results of two models were shown in the submitted version).

- *p.10, l.9: ”similar results have been obtained for other ones” ! ”similar results have been obtained for other climate models”?*

This sentence will be modified as suggested.

- *p.10, l.9-10: ”The results for CESM ensemble” ! ”The results for the CESM ensemble”*

This will be corrected, thanks.

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?*

The reference will be added in the revised version.

- *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.*

For us, the most important point is that the skill of the climate models can be tested despite the contribution of internal variability and the uncertainty in OGGM parameters or boundary conditions. A disagreement between observed and simulated glacier length for the ‘robust diagnostics’ indicates thus likely a climate model bias. This bias could be either on simulated temperature or precipitation, which are the two driving climatic variables in OGGM (a disagreement due to insolation changes would have an effect only indirectly as it is accounted in OGGM through the effect of insolation on temperatures). Nevertheless, if an independent comparison between simulated and reconstructed temperature confirms the underestimation of temperature changes, it is compatible with the hypothesis that a bias in temperature is at the origin of the underestimation of glacier length fluctuations. To underline that our hypothesis about a role of temperature changes, as discussed here, does not at all discard a potential contribution of other variables, those sentences will be reframed in the revised version as:

‘Nevertheless, some diagnostics appear robust enough for assessing the overall climate models skill in the region studied. In particular, some simulations underestimate the amplitude of the glacier changes between the 18th century and the end of the 20th century. This disagreement may have several origins, such as model biases in temperature or precipitation changes.

However, an independent comparison between simulated and reconstructed temperature suggests that those models have a too weak warming over the past two-three centuries, suggesting an important contribution from this variable in the glacier model behavior.'

- *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?*

This is indeed potentially interesting to compare the conclusion from the Alps to other regions but our simulations are only for the Alps and the evolution of glacier length is geographically complex. We would thus be obliged to make strong hypotheses and the resulting discussion would not be very informative. Therefore, we consider that this comparison is out of the scope of our manuscript and prefer to let this point to future studies.

- *p.11, l.18: "simulated and observed values". What does "values" refer to here? Climate or glacier length?*

This is glacier length. This will be specified in the revised version.

- *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?*

We are sorry that this sentence was unclear. This is related to a point raised above in a paragraph that we proposed to rephrase. The difference is simply due to the long response timescales of the glaciers. This will be mentioned explicitly in the revised version.

- *p.11, last sentence: consider adding "...of past climate reconstructions"*

This will be added in the revised version.

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.*

The figures will be updated using more distinct colors as suggested.

- *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.*

The thickness of the line corresponding to observations will be thicker in the revised version.

- *Fig.2, caption: "The reference period is 1901-1930": drop "the years" (cf. caption Fig. 3)*

The captions will be modified as suggested.

- *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.*

We agree that showing the observations as a horizontal line will make the figure easier to interpret. This will be done for the revised version.

• 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.

A larger black square will be used for observations in the revised version. Additionally, in the submitted version, we made the link with temperatures averaged over the whole Europe while in the revised version we will show the temperature averaged over the Alps. This does not modify the conclusions but this choice is more logical as it is the local temperature variations that are important for the glaciers.

References

PAGES Hydro2k Consortium, 2017. Comparing proxy and model estimates of hydroclimate variability and change over the Common Era. Clim. Past, 13, 1851-1900, https://doi.org/10.5194/cp-13-1851-2017.

Seftigen K., H. Goosse, F. Klein, and D. Chen, 2017. Hydroclimate variability in Scandinavia over the last millennium - insights from a climate model-proxy data comparison. Climate of the Past 13, 1831–1850, https://doi.org/10.5194/cp-13-1831-2017.

Response to reviewer 3

The Referee's comment below are in italics, our answer in plain font

The paper by Goose et al. applies the OGGM model to test glacier length changes using simulated climatology and compares the results to geologic observations. I have provided my technical comments as a .pdf. Overall, I find the paper easy to read, the figures to be mostly clear, and the general conclusions interesting enough to be published in Climate of the Past as it will be of interests to a broad readership to data generators and modelers alike. There are still some open questions that I've provided to the authors, but overall I think this paper will make a nice addition to the literature. I enjoyed reading it and as a data collector I find what they are modeling and testing to be of interest.

We would like to thank the Referee for the positive evaluation of our manuscript and for the suggestions. The technical corrections will be implemented in the revised version. We will also include all the suggested references in the revised version, except from the suggested citation on page 8: 'Gibbons et al. 1984 Geology'. We do not plan to include the later one as we were not able to find a corresponding reference that would match with our text.

Our answers to the general points included in the supplement are:

Page 8: It would be useful to include some of the Solomina et al. 2016 interpretations onto one of the figures. At the moment the connection between this part of the text and the figures is hard to understand. Also, Solomina et al. is a general review and I would suggest citing some original literature for the Alps from which they base their conclusions.

Fig. 5 of Solomina et al. (2016) clearly shows the periods of global glacier advances but, when focusing on a region like the Alps, the signal becomes very noisy (see figure 4 of Solomina et al. 2016) because of the smaller number of records, the discontinuities in those records and the difficulty to interpret some of them in a quantitative way. We have tried to include the information provided in Fig. 5 of Solomina et al. (2016) on our Figure 5 but with very limited success. Consequently, we decided to not include it in the revised version information directly on the figures but to modify the text to make the interpretation more straightforward. We will also cite some of the original literature as suggested.

Page 9: I agree that the investigation period is shorter, but the temperature changes is much larger. I was very surprised to see that the relationship between the summer temperature and the glacier length breaks down over the last 100 years (i.e. Figure 6a). I think a bit more explanation is warranted here since there appears to be no strong relationship between the warming, which is the largest of the last 1000 years, and the glacier lengths.

Do you really think it is because of the short period of investigation given that glacier retreat across the world is well documented (e.g. Oerlemans, 2005)? I guess I'm generally confused why this is the case but perhaps I'm missing something. This seems like a major point to address if you are going to conclude that there exists a dominate temperature control on glacier length.

The changes between 1700-1850 and 1970-2000 are larger on average by a nearly a factor 2 than the changes between 1970-2000 and 1900-1930. In addition to this larger signal, the longer averaging period allows to reduce the contribution of internal climate variability and the impact of the long response time of the glaciers. The variability of precipitation is also much higher for short periods than for longer ones. This explains why the link between temperature and glacier length appears relatively clearly for the longer period while it seems weaker for the shorter ones.

Nevertheless, the influence of temperature is still strong over the 20th century. The large majority of the glaciers are retreating over this period in the simulations driven by all the climate models (Sup. Fig 1), except in some members of CESM that have a very low warming. Consequently, our results are compatible with the observed glacier retreat across the world. It is just that the link between temperature and glacier length is more direct for longer timescales than when comparing two 30 year periods over the 20th century. This will be explained in more details in the revised version of the manuscript, adding a specific paragraph devoted to this point:

‘The warming over the 20th century has a clear impact on glacier length, inducing a simulated retreat of nearly all the glaciers in agreement with observations, except in some experiments driven by CESM members that display a weak temperature increase over the Alps (Fig. 3 and Sup. Fig. 1). Nevertheless, the contemporaneous temperature does not appear to be the only variable driving the glacier length changes when comparing two 30-year period at the beginning and the end of the 20th century (Fig. 6a). The contribution of temperature is present but the response time of the glacier as well as the influence of precipitation variability, for instance, can still obscure the link between temperature and glacier length for those relative short periods.’

The panels in Figure 2 are difficult to see in both the printed and .pdf versions. I would suggest finding a way to expand them to help the reader see them better.

To clarify in Figure 2 caption - the shaded region is the range and not the standard deviation about the mean?

Also, it a little disconcerting that the CESM ensemble are so far off the others during the last 100 years. The reason is obvious when looking at the temperature reconstructions (Figure 1) where the ensemble produces a late response to the abrupt climate warming. This makes me wonder about the utility of the CESM ensemble in general.

For the revised version, the panel of Figure 2 will be expanded.

Yes, as mentioned in the caption, the shaded area is the range of the ensemble.

We had no a priori in the selection of the models except the data availability and the absence of spurious trends or discontinuity in 1850 (see the method section). The difference between the results of OGGM driven by CESM results and observations is for us an interesting conclusion and including CESM results shows the interest of the proposed approach to evaluate the skills of climate models. We should insist that the performance of CESM is good for many characteristics of the climate of the last millennium (Otto-Bliesner et al. 2016) and there were no reason to suspect this behavior. For the ensemble itself, having an ensemble for all the models would be the ideal solution but it is unfortunately not the case. Nevertheless, different processes may control the amplitude of the internal variability, as measured by the range of the ensemble, and the forced response governing the trends over the past two centuries. The range of CESM provides thus one estimate of the role of internal variability but this is only one estimate and it must be taken with caution as discussed in section 3 (Page 7, line 16-20 of the submitted manuscript).

Figure 5 - I don't find this figure particularly helpful and overall it is a very confusing figure.

We agree that Figure 5 is not as clear as the other figures but it is helpful in order to make the comparison with equivalent figures produced from observations (as in Solomina et al. 2016). It also shows that the timings of advances and retreat are strongly influenced by internal variability so we propose to keep it in the revised version.

Testing the consistency between changes in simulated climate and Alpine glacier length over the past millennium

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Mis en forme : Français (Belgique)

Mis en forme : Anglais (États-Unis)

Mis en forme : Anglais (États-Unis)

Abstract. It is standard to compare climate model results covering the past millennium and reconstructions based on various archives in order to test the ability of models to reproduce the observed climate variability. Up to now, glacier length fluctuations have not been used systematically in this framework even though they offer information on multi-decadal to centennial variations complementary to other records. One reason is that glacier length depends on several complex factors and so cannot be directly linked to the simulated climate. However, climate model skill can be measured by comparing the glacier length computed by a glacier model driven by simulated temperature and precipitation to observed glacier length variations. This is done here using the version 1.0 of Open Global Glacier Model (OGGM) forced by fields derived from a range of simulations performed with global climate models over the past millennium. The glacier model is applied to a set of Alpine glaciers for which observations cover at least the 20th century. The observed glacier length fluctuations are generally well within the range of the simulations driven by the various climate model results, showing a general consistency with this ensemble of simulations. Sensitivity experiments indicate that the results are much more sensitive to the simulated climate than to OGGM parameters. This confirms that the simulations of glacier length can be used to evaluate the climate model performance, in particular the simulated summer temperatures that largely control the glacier changes in our region of interest. Simulated glacier length is strongly influenced by the internal variability of the system, putting limitations on the model-data comparison for some variables like the trends over the 20th century in the Alps. Nevertheless, comparison of glacier length fluctuations on longer timescales, for instance between the 18th century and the late 20th century, appear less influenced by the natural variability and indicate clear differences in the behaviour of the various climate models.

1 Introduction

As it offers a longer perspective compared to the so-called instrumental period (from roughly C.E. 1850 to present), the past millennium is a key period to study decadal to centennial climate variations. The syntheses of the available climate records indicate a general temperature decrease from the beginning of the second millennium to the beginning of the 19th century, followed by a large warming over the 20th century (Jones et al., 2009; Mann et al., 2009; PAGES 2k Consortium, 2013; Neukom et al., 2014; Pages2k Consortium, 2017). Nevertheless, the spatio-temporal structure of the temperature changes is complex, with warm and cold periods being generally not synchronous between different regions (PAGES 2k Consortium, 2013). Those conclusions are in overall agreement with the results derived from global climate models driven by estimates of natural and anthropogenic forcings, although models tend to underestimate the magnitude of the changes in some regions and to simulate more homogenous changes than in the reconstructions (Goosse et al., 2005; Raibble et al., 2006; Gonzalez-Rouco et al., 2006; Jungclaus et al., 2010; Phipps et al., 2013; Fernández-Donado et al., 2013; Landrum et al., 2013; Neukom et al., 2014; Moberg et al., 2015; PAGES2k-PMIP, 2015; Otto-Bliesner et al., 2016).

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The data syntheses covering the past millennium are based on many different archives such as trees, corals, glacier ice, lake sediments, pollen, speleothems, and marine sediments. They generally do not include glacier length fluctuations, although the latter can be used for independent tests of reconstructed changes (Guiot et al., 2010; Luterbacher et al., 2016). Glaciers are complex recorders of past conditions. Their fluctuations depend on the surface mass balance, which is ~~mainly~~ influenced by several factors including temperature, ~~and~~ precipitation and incoming radiation changes over the glacier, as well as ~~of~~ by the glacier dynamics and thus local geometry (Oerlemans, 2001; Huss et al., 2008; Roe, 2011). Furthermore, because of their long response time, glaciers integrate forcing over ~~timescales~~ periods ranging from a few years to several decades or even centuries (e.g., Jòhannesson et al., 1989; Leysinger Vieli and Gudmundsson, 2004). Consequently, glacier length fluctuations cannot be directly compared to records with a much faster response or simply included in multi-proxy reconstructions of past climate changes (Oerlemans, 2005; Roe, 2011; Solomina et al., 2016; Roe et al., 2017).

Despite those difficulties, it is possible to estimate the temperature and precipitation variations that were at the origin of the glacier length fluctuations (Mackintosh et al., 2017). One method is to drive a glacier model with a range of climate conditions to determine the ones that are compatible with the glacier length records (Allison and Kruss, 1977; Oerlemans, 1986; Jomelli et al., 2011; Leclercq et al., 2012; Luthi, 2014; Malone et al., 2015; Sagredo et al., 2017; Zechetto et al., 2017; Doughty et al., 2017). The temperature and precipitation reconstructions deduced from glacier length fluctuations can also be compared to estimates obtained from other records and climate model results to test the compatibility between the different sources of information. At large scale, temperature reconstructions have been obtained using simple glacier models in inverse mode (Oerlemans, 2005; Leclercq and Oerlemans, 2012), assuming that the selected glaciers are mainly influenced by temperature. However, the inversion required to obtain a temperature or a precipitation reconstruction from observations can be ill-conditioned if the record is influenced by several environmental factors, as it is the case for glacier length. It thus might be very difficult to disentangle, for instance, the contribution of changes in precipitation and temperature, leading to large uncertainties or biases in the reconstructed signal (Evans et al., 2013; Leclercq and Oerlemans, 2012; Mackintosh et al., 2017). An alternative method is to drive ~~directly~~ a glacier model directly with climate model results and compare the simulated length with the observed one. A similar approach, in which a proxy system model has been applied to simulate directly the observed quantity, has been successfully applied to a wide variety of variables such as tree ring widths, coral or speleothems composition

(Evans et al., 2013; Dee et al., 2015). The advantages are that the comparison is made on exactly the same variable for models and observations and that the problems related to an inversion are avoided. Until now, comparisons of climate model results with glacier length over the past millennium and the Holocene have been rare and the few existing studies were focused on a small number of glaciers (Weber and Oerlemans, 2003; Leclerq et al., 2012). This limits the ability to assess the climate model performance from glacier length records and the analysis of the origin of observed glacier changes using climate model results. In addition to the simulated climate, the quality of the comparison between modelled and observed glacier lengths depends on several factors that need to be addressed. First, glacier models have their own limitations (Huss and Hock, 2015; ~~Farinotti et al., 2017;~~ Maussion et al., 2018) and some of the disagreements between simulated results and observations might be attributed to the glacier model and its initial/boundary conditions (e.g. Farinotti et al., 2017) rather than to the climate model. An additional source of uncertainty is related to the internal variability of the climate, which can be dominant at regional scale for the past millennium (Goosse et al., 2005; Jungclaus et al., 2010; Goosse et al., 2012a; Otto-Bliesner et al., 2016). As the climate fluctuations are integrated by the glaciers, this induces glaciers length changes reaching potentially several hundreds of meters (Oerlemans, 2000; Roe et al., 2009; Roe, 2011; Barth et al., 2018). ~~Because of the chaotic dynamics of the climate, climate models are not expected to reproduce the timing of the observed events associated to internal variability, leading to some unavoidable differences with observations.~~

Our goal here is to perform a systematic evaluation of climate models behavior by using the outputs of simulations covering the past millennium to force a global glacier model (Maussion et al., 2018). The main objective is to provide a new validation procedure for climate models complementary to the existing ones. Specifically, we will estimate the compatibility of the simulated multi-decadal to centennial scale climate variability with glacier length records, analyzing the links between glacier fluctuations and ~~modelled as well as reconstructed~~ temperature changes. This implies an estimation of the sources of uncertainty associated with glacier modelling and of the contribution of internal variability to simulated changes. Additionally, the comparison will provide a test of our ability to reproduce past glacier variations using tools that are similar to the ones applied to estimate future changes in glaciers and their contribution to sea level rise (e.g. Marzeion et al., 2012; Gregory et al., 2013; Bliss et al., 2014; Huss and Hock, 2015; Slangen et al., 2016; Marzeion et al., 2018). The initial focus is here on European glaciers and more specifically on the Alps because of the availability of records that are long enough for our analyses.

The climate model results, the glacier model and the glacier length observations are described in section 2. The results of the glacier model driven by a range of climate models are compared with observations in section 3. This includes a discussion of the contribution of internal variability to glacier fluctuations and its impact on the conclusion of model-data comparison. The sensitivity of the results to key parameters of the glacier model and to the experimental set up are discussed in section 4. Final conclusions are proposed in section 5.

2 Methods

2.1 Climate model results

The climate variables used to drive the glacier model are derived from simulations following the Past Model Intercomparison Project (PMIP3) and the Coupled Model Intercomparison Project (CMIP5) protocols (Schmidt et al., 2011; ~~Otto-Bliesner et al., 2009;~~ Taylor et al., 2012; PAGES2k-PMIP3, 2015). They were downloaded from the Program for Climate Model Diagnosis and Inter-comparison (PCMDI; http://pcmdi9.llnl.gov) and the Earth System Grid (www.earthsystemgrid.org) archives. We have selected the same simulations as in Klein et al. (2016). Some of those simulations are not continuous in 1850 between the ~~so-called~~experiments referred to as ‘past1000’ in CMIP/PMIP nomenclature ~~past1000~~ (years 851-1850) and the ‘historical’ (years 1851-2005) simulations. Because of this discontinuity associated with the experiment design, a ~~but the~~ jump can be present on the simulated variables in 1850, but it is relatively small for the selected experiments so they can be merged with a limited impact on the results. Those simulations are driven by natural (orbital, solar, volcanic) and anthropogenic (greenhouse gas, ozone, aerosol, land-use) forcings (Schmidt et al., 2011; Schmidt et al., 2012). Nevertheless, the simulations performed with BCC-CSM1-1 and IPSL-CM5A-LR do not include land-use forcing. Additionally, the aerosol forcing is not activated in the IPSL simulation. One simulation for CCSM4, GISS-E2-R, IPSL-CM5A-LR, MPI-ESM-P and BCC-CSM1-1 and an ensemble of 10 simulations with CESM1 are used here. More details about the simulations and the forcing applied in each of them can be obtained in Klein et al. (2016) and PAGES2k-PMIP3 (2015).

2.2 The Open Global Glacier Model

The Open Global Glacier Model (OGGM, Maussion et al., 2018) is an open source model that simulates the evolution of individual glaciers, explicitly accounting for glacier geometry, even in complex configurations involving contributory branches. The first step is to describe the glacier outlines and topography from global public data bases: the RGI version 5 (RGI Consortium, 2015) and SRTM topography data version 4 (Jarvis et al., 2008). The glacier main branches, tributaries and flowlines are then defined and the glacier ice thickness estimated solving the equations of ice flow and mass-conservation along the flowline.

The mass balance is computed from the equation (Marzeion et al., 2012):

$$m_i(z) = p_f P_i^{solid}(z) - \mu * \max(T_i(z) - T_{melt}, 0) + \varepsilon \tag{1}$$

where $m_i(z)$ is the mass balance of month i at the altitude z. $P_i^{solid}(z)$ is the monthly solid precipitation and $T_i(z)$ the monthly mean temperature. The amount of solid precipitation is derived from the total amount of precipitation assuming that precipitation are entirely solid below 0°C, entirely liquid above 2°C and the fraction of solid precipitation varies linearly with temperature between those two values. p_f is a correction factor included to take into account the larger precipitation over the glaciers than in the surrounding terrain and at lower altitudes where observations are available. Its value is constant for all the glaciers and taken equal to 2.5 (e.g., Giesen and Oerlemans, 2012). Melting occurs if monthly temperature is above T_{melt}, which

Code de champ modifié

is equal to -1°C in OGGM, as melting may occur some days even though the monthly mean is below 0°C. This value has been selected on the basis of a cross-validation procedure similar to the one conducted by Marzeion et al. (2012). μ* is the temperature sensitivity parameter and ε a residual bias. μ* and ε are ~~is~~ estimated first for glaciers where mass balance observations are available and then extrapolated to the other glaciers following a procedure described in Marzeion et al. (2012) and Maussion et al. (2018).

The ice dynamics is based on the shallow-ice approximation and is computed along the flowline. In the shallow ice approximation, the vertical variations of ice flow are neglected and only a depth-integrated ice velocity is computed. This is a common approximation for computationally efficient ice flow models, and it is largely valid as long as the considered horizontal scales are much larger than the vertical scales (Hutter 1981, 1983). Basal sliding is also neglected here. For the prefrontal areas, the direction and path of ice flow are obtained by computing the route from the glacier tongue toward the end of the domain that is the least costly in terms of positive altitudinal change. The flowline therefore follows the valley as a river would do. Along this flowline, we estimate the shape of the bed by fitting a parabola to the intersection points between the actual topography and the normal to the flowline. A main parameter of the model is the creep parameter *A*. A low value of *A* corresponds to stiff ice, low velocities and generally a higher ice volume while high value of *A* is associated with softer ice and leads to a faster flow and lower ice volumes. The standard value of *A* selected in OGGM is constant for all glaciers and set equal 2.4 10^{-24} s^{-1} Pa^{-3}~~.~~, while in reality *A* may change by a factor 10 between glaciers~~,~~ due to a wide range of processes ~~in particular because of changes in their temperature~~ (Cuffey and Paterson, 2010).

One advantage of OGGM is that it can be applied to any glacier. It does not require any specific detailed information that would be lacking for the majority of them. Besides, it includes simplifications compared to models focused on a particular well-observed glacier (e.g., Zekollari et al., 2014) and is therefore computationally efficient.

The climate model outputs required to drive OGGM are the monthly mean temperature and precipitation. The local temperature is obtained assuming a constant lapse rate of 6.5 K km^{-1}. To take into account the biases of the climate model, a simple correction procedure is applied: the model results are adjusted to have the same climatological monthly mean values over the reference period 1900-2000 as in the Climatic Research Unit (CRU) Dataset (New et al., 2002; Harris et al., 2014) used in the standard version of the model (Maussion et al., 2018). The simulations cover the period 850-2005, corresponding to the past1000 and historical simulations in the PMIP3/CMIP5 protocol. However, ~~as~~ the sensitivity tests that we have performed have shown that the first century is influenced by the choice of initial conditions for the selected glaciers~~,~~. Consequently, we will only present the results after 1000 CE.

2.3 Glacier length observations

Glacier surface mass balance is the variable that is the most directly related to climate but only a few, generally short, records are available (Zemp et al., 2009). The number and duration of glaciers length observations are much larger (Oerlemans, 2005; Leclercq et al., 2014; Zemp et al., 2015; Solomina et al., 2016). The most accurate estimates are deduced from direct observations of the glacier terminus position as recorded for instance by the World Glacier Monitoring Service in the

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Fluctuations of Glaciers (~~www.wgms.ch, ~~WGMS, 2017). The modern observations can be complemented by historical sources including old maps, painting, drawing and early photographs as well as written documents (Grove, 2004; Nussbaumer and Zumbühl, 2012; Purdie et al., 2014; Zumbühl and Nussbaumer, 2018). Additional evidence is obtained by dating the position of moraines indicating the position of the glacier at specific times or from the trees that have been overridden by the advance of a glacier (Masiokas et al., 2009; Ivy-Ochs et al., 2009; Wiles et al., 2011; Schimmelpfennig et al., 2014; Le R~~r~~oy et al., 2015; Moran et al., 2017).

As the comparison of model results with observational estimates is a key element of our methodology, we have applied OGGM on 71 glaciers from the European Alps that have records covering at least the 20th century in the global compilation of Leclercq et al. (2014). 12 of those glacier length series goes back to 1800 CE, 7 to 1700 CE and the longest record starts in 1535 CE (Unterer Grindelwald), allowing for each of them a quantitative comparison with model results at multi-decadal to centennial timescales. The complete list of glaciers is provided in the supplementary material (Table S1). Longer records are also available for many glaciers but are discontinuous and more uncertain, as reviewed in Solomina et al. (2016). Some of those records will be used for a qualitative evaluation of our results.

3. Simulated ~~and reconstructed ~~glacier changes

Enhanced winter precipitation has been suggested to be an important contributor to some past changes in glacier length in the Alps (e.g., Vincent et al., 2005; Steiner et al., 2005; Steiner et al., 2008). Nevertheless, summer temperature is generally considered as the major driver of European glacier fluctuations at centennial timescales (Oerlemans, 2001; Steiner et al., 2005; Huss et al., 2008; Steiner et al., 2008; Leclerq and Oerlemans, 2012; Zekollari et al., 2014). ~~As summer temperature is a major driver of European glacier fluctuations (Oerlemans, 2001; Huss et al., 2008; Steiner et al., 2008; Leclerq and Oerlemans, 2012; Zekollari et al., 2014), ~~I~~i~~t is thus instructive to compare first the simulated temperatures with reconstructions before analysing the glacier themselves. Europe is probably the continent where the density of records of past temperature changes is the highest and several large scale reconstructions are available (Luterbacher et al., 2004; Guiot et al., 2010; Pages2k Consortium, 2013; Luterbacher et al., 2016). For simplicity, we will only discuss here the most recent spatial reconstruction of summer temperature, which is highly correlated with long thermometer observations and the majority of individual records (see Luterbacher et al., 2016 for more details).

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In agreement with previous studies (Raible et al., 2006; Hegerl et al., 2011; Goosse et al., 2012b; PAGES2k-PMIP3, 2015; Luterbacher et al., 2016), most models are able to reproduce the relatively warm conditions observed at continental scale during the first centuries of the millennium, the cold conditions around 1600-1800 and the large warming of the 20th century (Fig. 1). However, they underestimate the magnitude of the changes for some (multi-)decadal scale events compared to the reconstruction of Luterbacher et al. (2016). Interestingly, some models display an industrial-era warming that occurred earlier or later than observed (Abram et al., 2016), with a potentially large impact on the glacier retreat over the recent period. At regional scale for the Alps, the conclusions are similar except that the internal climate variability becomes large enough so that simulation results cover nearly the full range provided by the reconstruction, even for the decadal-scale warm or cold events.

The comparison between OGGM results driven by the various climate models and observations leads to contrasted results for individual glaciers (~~see~~ Supplementary ~~Figure~~ Fig. 1). This was expected as we have not modified or adapted specifically the parameters in order to apply strictly the standard configuration of the model in this first set of simulations. Nevertheless, for the large majority of the glaciers, the observed length changes are well within the range simulated by the model. For some others, all the simulations overestimate or underestimate the trends over the 20th century or the variability in the pre-industrial period. This is illustrated for five well-known glaciers on Figure 2, but a similar behaviour is seen for many other ones (see Supplementary Fig. 1). In those examples, the models tend to underestimate the retreat of the Unterer Grindelwald and Mer de Glace during the 19th century but some of them have a larger retreat than observed for those two glaciers over the 20th century. The agreement is better for the Hintereis, Great Aletsch and Bossons glaciers although for the latter most models overestimate the magnitude of the changes compared to observations.

A detailed comparison between simulations and observed results for each glacier is out of the scope of the present study as differences may have their origin in the specific characteristics of the glacier such as its stiffness or the presence of debris, in the links between the local climate and large scale changes, in uncertainties in the calibration of the climate sensitivity parameter of OGGM, etc. However, a behaviour common to the large majority of the glaciers can be associated to a particular climate model and can be described by simply performing the mean changes over all the glaciers. Conclusions are qualitatively similar for the mean of absolute changes (Fig. 3~~-~~a) and the mean of relative changes (Fig. 3~~-~~b). For ~~this~~ these latter diagnostics, the glacier length changes are normalized using their observed length in 1950 before performing the average. This implies that the absolute mean is not dominated by the long glaciers with large fluctuations but reflect a general signal present in the majority of glaciers.

For some climate models (as the IPSL model), OGGM simulates a relatively stable mean glacier length in the preindustrial period. When driven by the other climate model outputs, the growth trend between 1000 and 1850 is larger, in particular for the GISS model, CESM and CCSM4. This is followed by a large retreat starting in the 19th century, except in CESM for which the melting begins in the 20th century for nearly all members.

Visually, the difference between simulated glacier lengths (Fig. 3) appears much larger than for the temperature (Fig. 1), suggesting that glacier length provides a clear constraint on climate model behaviour. However, part of it may be related to the way the figure is presented. In particular, using a reference period in the 20th century, as required because of the short duration of the glacier records, tends to amplify the differences in the preindustrial period compared to the classical reference period chosen for temperature (Fig. 1). This is illustrated in Supplementary Figure 2 in which temperature series have been plotted with a reference period in the 20th century.

Additionally, some of the differences between the simulated glacier lengths may be due to the integration of the internal climate variability by the glaciers and not to a systematic difference between climate models. This impact of internal variability can be quantified from the ensemble of simulations performed with CESM. We have to be careful since this estimate is derived from one model only, which displays significant differences with the some of the other models for the Alps. Nevertheless, this provides a first order estimate.

The glacier retreat over the 20th century varies strongly between CESM ensemble members, with the observed changes in the ~~upper~~ lower range of the ensemble (Fig. 4a). Consequently, although the magnitude of the changes ~~vary~~ varies considerably between simulations, it is impossible to reject firmly the hypothesis that the differences between climate models and between models and observations for the Alps over this period are due to internal climate variability only.

The signal is clearer when comparing the late 20th century with the years 1700-1850 (Fig. 4b), which roughly corresponds to the maximum extent in the simulated results. All the simulations driven by CESM underestimate the observed changes between those two periods, as the simulated glacier retreat starts much later than in the observations (Fig. 3). The simulations using the standard version of OGGM driven by the other ~~GCMs~~ climate models are at the margin or out of the CESM ensemble range, suggesting that the difference are not only due to internal climate variability but are related to different characteristics of the simulations performed with the various climate models. Those simulated results are closer to observations, in particular the ones driven by CCSM4, IPSL and BCC model results.

Computing the difference between the years 1000-1150 CE (Fig. 4c), when the glacier extent was close to its minimum in nearly all the simulations, and the years 1700-1850 CE confirms the differences deduced qualitatively from Fig. 3. Some models have a large positive growth trend over the preindustrial period while some others have a much smaller one, with potentially a very large contribution of internal variability. The comparison between the late 20th century and the beginning of the millennium reveals also some clear differences between the simulations (Fig. 4d). For some of them, as the ones driven by the IPSL and MPI models, the minimum is clearly reached in the late 20th century while many glaciers w~~h~~ere smaller during the period 1000-1150 CE in the simulations driven by CESM and GISS outputs. It is difficult to estimate from observations when glaciers w~~h~~ere smaller than presently as the evidence may still be buried under the ice (Goehring et al., 2011; Luthi et al., 2014; Solomina et al., 2016). For the Alps, this might have occurred before 1000 CE or in the periods 1200-1280 and 1400-1550 ~~AD~~ CE but there is currently no direct evidence that this actually took place during the past millennium (Luthi et al., 2014).

Another instructive diagnostic is the proportion of glaciers that are advancing over a specific period (Fig. 5), since it can potentially be compared to observations (e.g., Solomina et al., 2016). However, this diagnostics is by construction noisier than the glacier length itself and is strongly influenced by internal variability, with the simulations driven by CESM covering nearly the full range between 0 and 100 % of advancing glaciers for several periods. Estimates derived from observations also display uncertainties. The evidence for a glacier advance, as derived for instance from a moraine position, may actually correspond to a time where the glacier is close to a maximum extent rather than still advancing (Grove, 2004; Solomina et al., 2016). The absence of evidence of advance may also be only due to the lack of a preserved signal in geomorphological features, not to the glacier changes themselves. The model-data comparison can thus only be qualitative and must be interpreted with caution.

As described in the synthesis of Solomina et al. (2016) for the Alps, many glaciers display a minimum extent around the 9th-11th century. This is followed by a first advance in the 12th century, a retreat in the beginning of the 13th century and a general advance in the late 13th century (Holzhauser et al., 2005; Luthi et al., 2014; Le Roy et al., 2015). This advance after the 11th century is in general agreement with our results except that the majority of models simulate an increase in glacier length for the beginning of the 13th century too, while the 12th century is generally characterized by a small number of advances. This would suggest a wrong timing of the glacier advances in models and would be consistent with the higher simulated European temperatures compared to the reconstruction of Luterbacher et al. (2016) around 1100 CE and the lower simulated values compared to the reconstructed ones around 1200 CE. Nevertheless, the variability in the simulated results is too large to obtain a clear answer from the diagnostics of glacier advances alone.

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~~Despite those limitations, it is instructive to see that, in our simulations, many glaciers already advance in the first century of the second millennium. This is consistent with a minimum extent of glaciers around the 9th-11th century in the Alps (Luthi et al., 2014; Solomina et al., 2016). In their synthesis of records for the Alps, Solomina et al. (2016) suggest that a first advance occurred in the 12th century, followed by a retreat in the beginning of the 13th century and a general advance in the late 13th century. The latter advance is in agreement with simulated results. Nevertheless, the majority of models simulate an increase in glacier length for the beginning of the 13th century too, while the 12th century is generally characterized by a small number of advances. This would suggest a wrong timing of the glacier advances in models and would be consistent with the higher simulated European temperatures compared to the reconstruction of Luterbacher et al. (2016) around 1100 CE and the lower simulated values compared to the reconstructed ones around 1200 CE. Nevertheless, the variability in the simulated results is too large to obtain a clear answer from the diagnostics of glacier advances alone.~~

Subsequently, observational evidence indicates a retreat around 1400 CE before new advances in the late 15th century and the 16th century, their timing varying between ~~Alpine~~ regions ~~or glaciers~~ (Holzhauser et al., 2005; Schimmelpfennig et al., 2014; Luthi et al., 2014; Le R~~r~~oy et al., 2015; Solomina et al., 2016). The early 15th century is also a period with glacier retreats in models, preceding major advances in good agreement with observations. The variability between models is larger for the years 1500-1850, when the extent was close to its maximum, and no clear common signal can be deduced from the diagnostics of glacier advances in the simulations for this period.

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The early 15th century ~~that stands out as~~corresponds to a minimum for glacier advances in many models (Fig. 5) and ~~is also a period with~~ a relative minimum in glacier length (Fig. 3). Although ~~but~~ the simulated temperatures are generally mild ~~not very different from earlier or later period~~during this period, there are not high and, in particular, ~~are~~ are generally lower than in the beginning of the millennium (Fig. 1). This clearly illustrates ~~that~~ the impact of the ~~glaciers have a~~ long response timescales of glaciers. The simulated glacier retreats in the early 15th century ~~are~~ appear to be partly due to the ~~relatively mild conditions~~temperatures ~~in the late 15th century~~at that time but also to the recovery from the large advances in the 13th and 14th century.

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The ~~link is a bit less clear when focussed~~warming over the ~~on the~~ 20th century has a clear impact on glacier length, inducing a simulated retreat of nearly all the glaciers in agreement with observations, except in some experiments driven by CESM members that display a weak temperature increase over the Alps (Fig. 3 and Sup. Fig. 1). Nevertheless, the contemporaneous temperature does not appear to be the only variable driving the glacier length changes when comparing two 30-year period at the beginning and the end of the 20th century (Fig. 6a). The contribution of temperature is present but the response time of the glacier as well as the influence of precipitation variability, for instance, can still obscure the link between temperature and glacier length for those relatively short periods.~~,~~

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~~because the investigated period is shorter.~~

The association between summer temperature and glacier changes is ~~more~~ more ~~direct~~ direct and linear when analysing length changes on longer timescales. The relative minimum in glacier length in the 12th century (Fig. 3) is clearly due to the warm simulated temperatures at that time (Fig. 1). The climate models that have the largest temperature changes over the pre-industrial period and between pre-industrial period and the 20th century are also the ones that lead to the larger changes in glacier length (Fig. 6bcd).

~~The link is a bit less clear when focussed on the 20th century, because the investigated period is shorter. Nevertheless, t~~This confirms ~~the~~ a dominant role of temperature fluctuations on glacier evolution in the Alps (Oerlemans, 2001; Huss et al., 2008; Steiner et al., 2008; Leclerq and Oerlemans, 2012; Zekollari et al., 2014). Furthermore, although some simulations display smaller or larger values compared to observations for each variable, the model ensemble agrees very well with observations for the ratio between temperature and glacier length changes between the pre-industrial period and the 20th century (Fig. 6b). This suggests that the glacier model has a reasonable temperature sensitivity. An alternative interpretation is to state that the link between reconstructed temperatures and glacier length observations is compatible with model results using the standard parameters of OGGM.

4. Sensitivity of glacier changes to model parameters

The parameter set and experimental design applied in the simulations described in Section 3 are identical to the ones of the standard version of the OGGM model (Maussion et al., 2018). In order to estimate how our results are sensitive to this choice, a series of sensitivity experiments has been performed, addressing uncertainties on OGGM representation of the glacier dynamics, the surface mass balance and the way climate model results are processed before using them to drive the glacier model.

In the first two experiments, the creep parameter has been multiplied and divided by a factor two for all the glaciers, applying then a value of 4.8 10^{-24} s^{-1} Pa^{-3} and 1.2 10^{-24} s^{-1} Pa^{-3}, respectively. In the next two experiments, the climate sensitivity parameter μ* has been uniformly decreased and increased by 10%, respectively. Those experiments are not intended to correspond to a new calibration of those parameters but are used to provide a measure of the impact a variation in their range of uncertainty (Marzeion et al., 2012; Maussion et al., 2018).

In the standard simulations, a very simple bias correction is applied to climate model results, ensuring that after the adjustment the climate models have the same mean over the reference period than the CRU data set used to calibrate OGGM climate sensitivity parameter (see section 2). However, the variance and the magnitude of the response to a perturbation is likely different at the altitude of the glacier compared to the lower one corresponding to the land surface at the scale of the global climate model (Mountain Research Initiative EDW Working Group, 2015~~, ~~; Kotlarski et al., 2015). Consequently, we have scaled simulated temperatures in the final sensitivity experiment so that the variance for each month has the same value as for CRU dataset. The temperatures have not been detrended before computing the variance and this includes thus a scaling of the warming over the 20th century as well as of the interannual variability, but the correction is not time-scale dependent. This scaling does not only take into account the elevation dependence of the changes but also any bias in the simulated variance (~~Marum ~~Maraun and Widmann, 2018).

Those changes in parameters have a very large impact on glacier volume, in agreement with previous tests performed with OGGM (Maussion et al., 2018). The differences can reach up to a factor two compared to the standard experiment. They also have a clear impact on the mean length of the glacier. However, when discarding the first 150 years of simulations (when the adjustment to the new parameters occurs), the changes in glacier length averaged over the 71 glaciers are very small. This is illustrated for ~~two climate models~~CCSM4 in Fig~~.~~ ure 7. Similar results have been obtained for the other ~~ones~~climate models (not shown). ~~The results for CESM ensemble i~~In particular,~~ show that~~ the sensitivity to glacier model parameters and to the correction method applied to climate model results are much smaller than the contribution of internal variability (see Fig. 3), whose role as a dominant source of uncertainty in model-data comparison is thus confirmed. This conclusion is reached for the Alps and for the selected climate models. Different results might be obtained for other regions or for other models displaying larger biases. Additionally, sensitivity experiments with larger perturbations of parameters would lead to larger differences with the standard experiment. Nevertheless, the small changes in the results of our sensitivity experiments indicate that the main conclusions obtained in Section 3 are not critically ~~dependant ~~dependent of the choices made in the application of OGGM.

5. Conclusions

The simulations performed with OGGM driven by climate models results have shown that there is no inconsistency between the climate provided by the model ensemble and glacier lengths observations. Disagreements are found for individual glaciers but this was expected as global models are not able to represent the small scale processes that may rule some glacier changes. However, when analysing the 71 selected glaciers, there is no systematic bias in the timing or the amplitude of simulated glaciers changes and the observed length variations are generally well within the range of simulated values. This agreement was achieved without any specific calibration of the glacier model and does not appear critically dependent on the choice of some model parameters.

This provides an additional positive evaluation of climate models~~ over the past millennium~~, confirming using a new type of data their ability ~~of climate models ~~to reproduce the dominant changes over the past millennium. The successful application of global climate models driving a global glacier model over the past millennium also reinforces the validity of this approach to study future changes on similar timescales.

Some studies have argued that the large melting of Alpine glaciers in the 19th century might be due to a modification of the ice albedo caused by the deposition of black carbon of anthropogenic origin (Painter et al., 2013). This hypothesis has been recently challenged (e.g. Luthi, 2014), in particular because no evidence of a significant deposition at the time of the retreat was found in an ice core collected in the Alps (Sigl et al., 2018). Although the simulated changes are underestimated here for some glaciers, this additional forcing does not seem to be required systematically to reproduce past glacier changes in models.

In addition to the overall compatibility of the ensemble of simulations with observations, the comparison between simulated results and estimates of past glacier lengths fluctuations may help identifying some specific characteristics of individual climate model simulations. This comparison is complicated because of the large contribution of internal climate variability on glacier length fluctuations. Nevertheless, some diagnostics appear robust enough for assessing the overall climate models skill in the region studied. In particular, some simulations underestimate the amplitude of the glacier changes between the 18th century and the end of the 20th century. This disagreement may have several origins, such as model biases in temperature or precipitation changes. However, an independent comparison between simulated and reconstructed temperatures suggests that those models have a too weak warming over the past two-three centuries, suggesting an important contribution from this variable in the glacier model behavior. ~~Nevertheless, some diagnostics appear robust enough to identify a clear bias in climate models. In particular, some simulations underestimate the amplitude of the glacier changes between the end of the 20th century and the 18th century, which is consistent with a too weak temperature change between those periods compared to reconstructions in the driving climate model. It is impossible to determine from this diagnostic if the differences with observations is due to model biases for the pre-industrial period or over the recent one, but it is instructive for assessing the overall model skill in the region studied.~~

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Another robust characteristic of many simulations is the timing of the minimum glacier extent over the past millennium. For some climate models, this occurs clearly at the end of the simulation while for some other models the minimum extent takes place in the beginning of the millennium. Unfortunately, observations do not allow determining which behaviour is more realistic. Although there are not enough observations in the Alps to argue in favour of a systematic lower extent than today during some periods in the past millennium, the evidence is maybe still hidden below the ice.

More generally, our experiments have demonstrated the interest of driving a global glacier model by climate model outputs in order to have a direct comparison between simulated and observed ~~values~~glacier length. This allows a more quantitative evaluation of the models and a more precise interpretation of the records. For instance, the beginning of the 15th century is characterized by a general glacier retreat in simulations and reconstructions but without particularly high temperatures~~, ~~, illustrating that even though the link between summer temperature and glacier length is strong in the Alps, it is not always straightforward because of the long response time of glaciers. Our results thus open the application of the same approach to other regions and the integration of glacier records with other ones in multi-proxy assessments of past climate reconstructions.

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Code availability.

The code of OGGM (DOI: https://zenodo.org/record/1149701) is freely available online (http://oggm.org/).

Data availability.

Simulated Glacier lengths will be made available on a public repository (*address available for the final version of the paper*).~~when the paper will be accepted.~~

Competing interests.

The authors declare that they have no conflict of interest.

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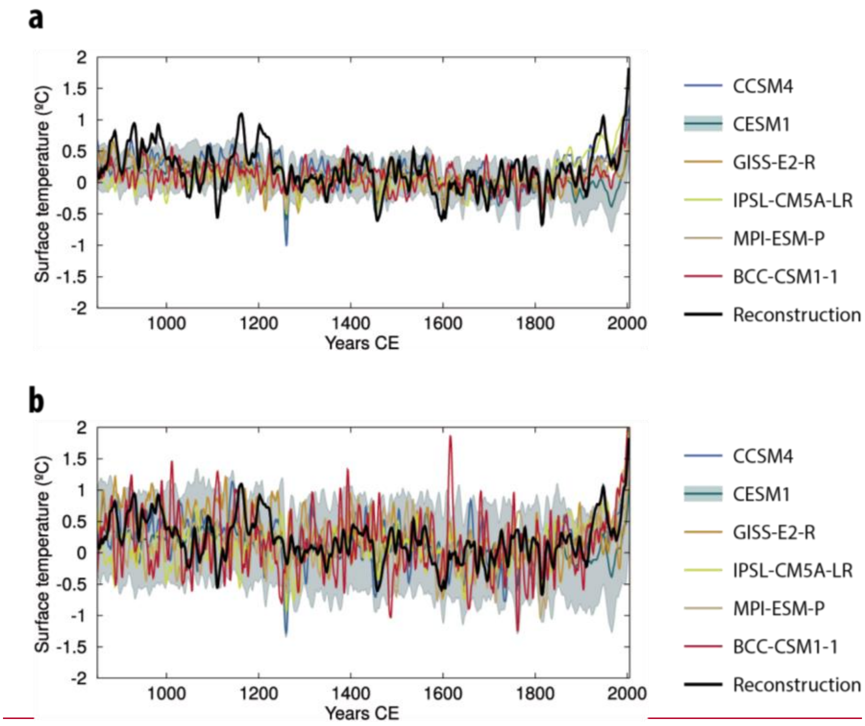
Table 1. Climate model simulations used to drive OGGM

Name	Institution	Resolution in the Atmosphere (lat x lon)	Reference
CCSM4	National Center for Atmospheric Research	192 x 288	Gent et al. (2011)
CESM1	National Center for Atmospheric Research	96 x 144	Otto-Bliesner et al. (2016)
GISS-E2-R	NASA Goddard Institute for Space Studies	90 x144	Schmidt et al. (2014)
IPSL-CM5A-LR	Institut Pierre-Simon Laplace	96 x 96	Dufresne et al. (2013)
MPI-ESM-P	Max Planck Institute for Meteorology	96 x 192	Stevens et al. (2013)
BCC-CSM1-1	Beijing Climate Center, China Meteorological Administration	64 x128	Wu et al. (2014)


a
Surface temperature (ºC)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1000
1200
1400
1600
1800
2000
Years CE
CCSM4
CESM1
GISS-E2-R
IPSL-CM5A-LR
MPI-ESM-P
BCC-CSM1-1
Reconstruction
b
Surface temperature (ºC)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1000
1200
1400
1600
1800
2000
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GISS-E2-R
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MPI-ESM-P
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Reconstruction

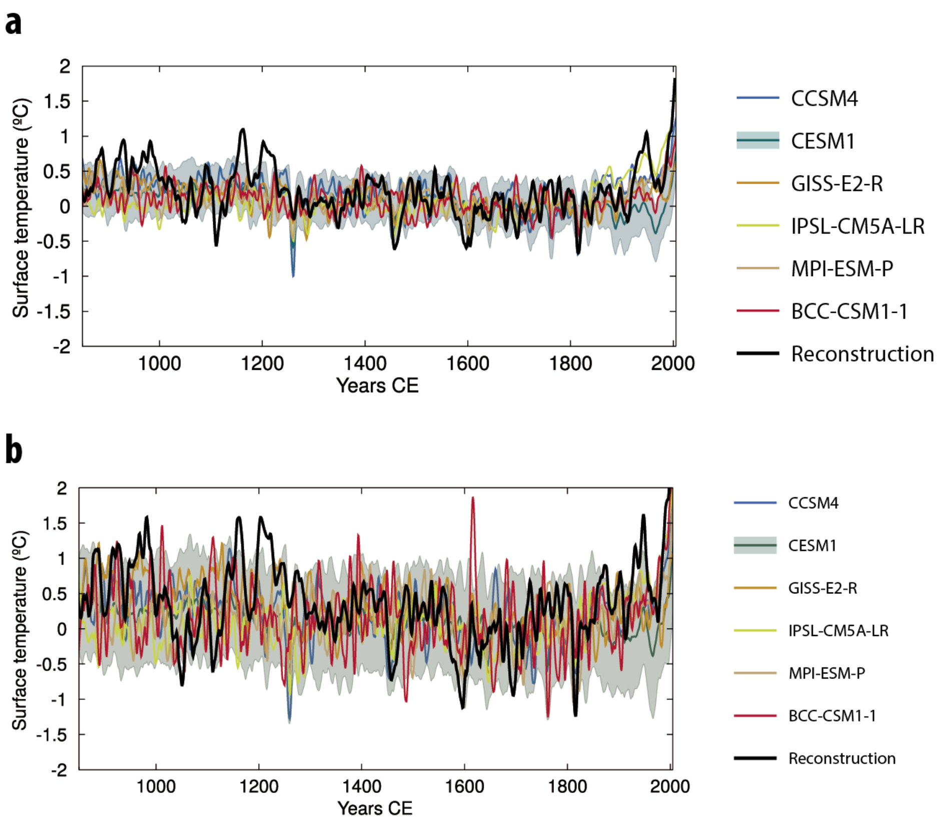
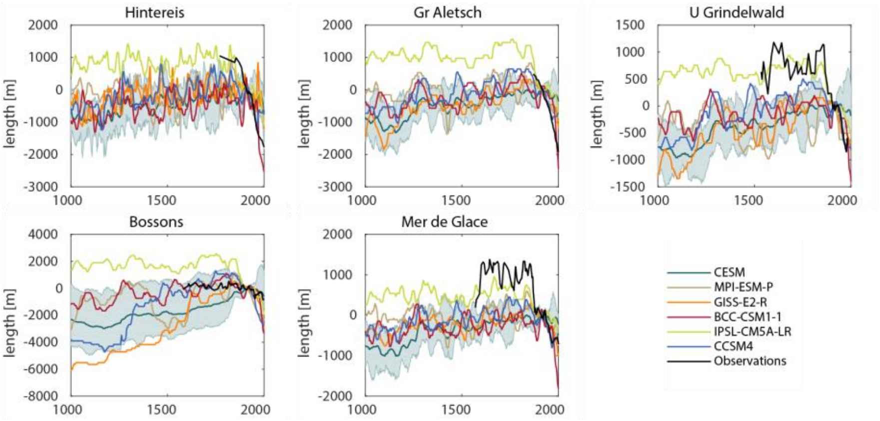


Figure 1. Summer temperature ~~overaged~~ averaged over a) Europe and b) the Alpine region (defined here as the area between 45 and 48°N and between 6 and 13°E) in the reconstruction of Luterbacher et al. (2016) and as simulated by climate models over the past millennium. The shaded area represents the mean plus and minus one standard deviation of the CESM1 model ensemble. A 15-year Lowess smoothing has been applied to the time series. The reference period is the years 1500-1850 CE as in Luterbacher et al. (2016).



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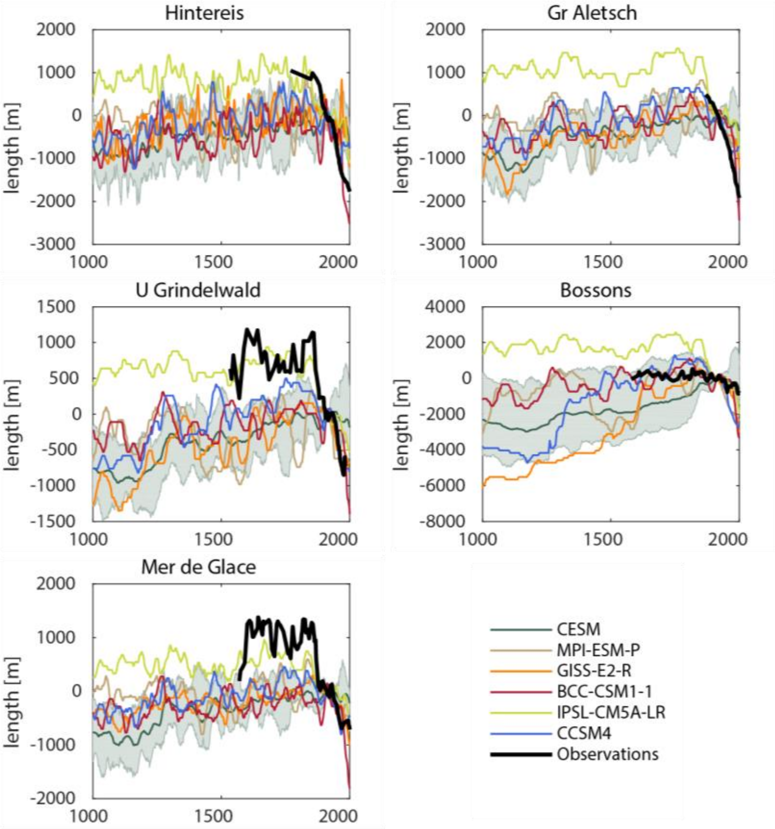
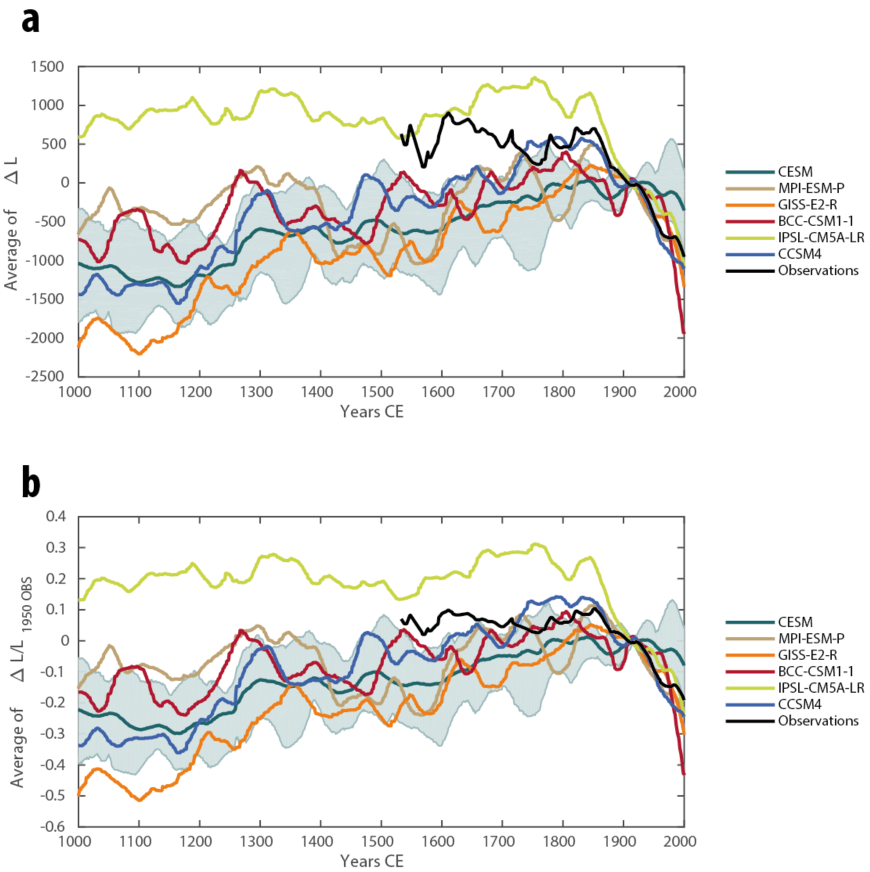


Figure 2. Observed and simulated length for five selected glaciers in the Alps. The shaded area represents the range of the ensemble of simulations driven by CESM outputs. The reference period is ~~the years~~ 1901-1930 CE.



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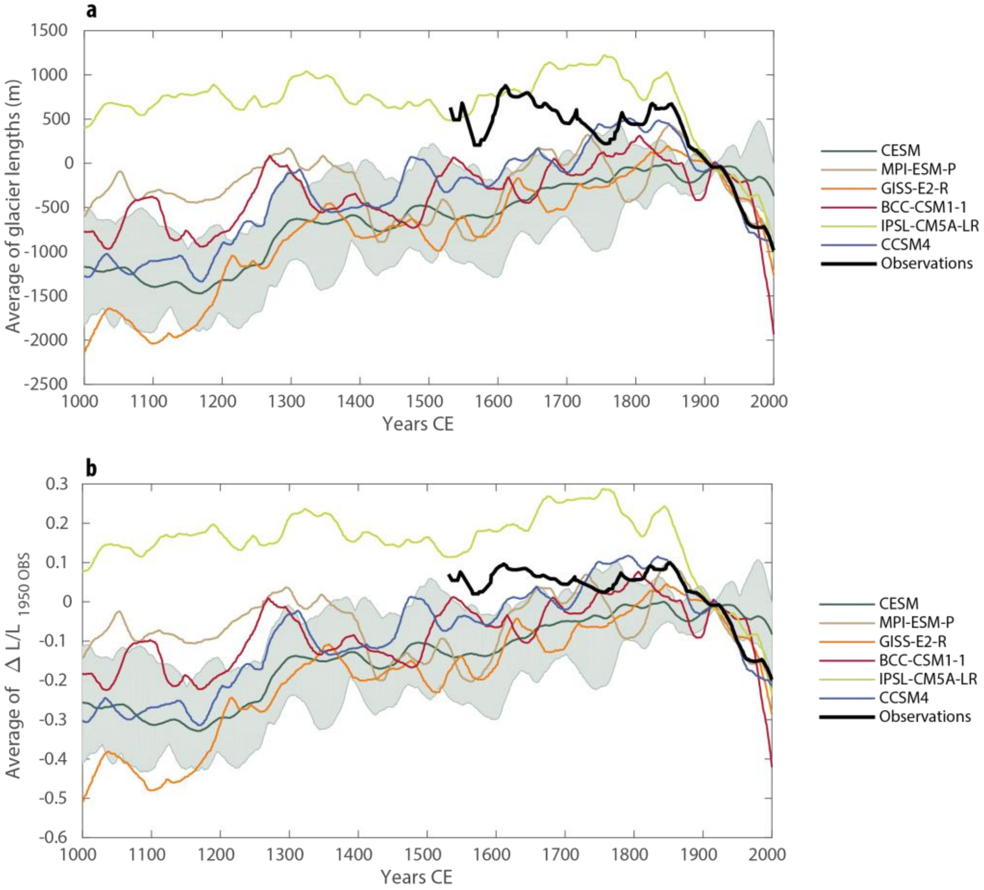
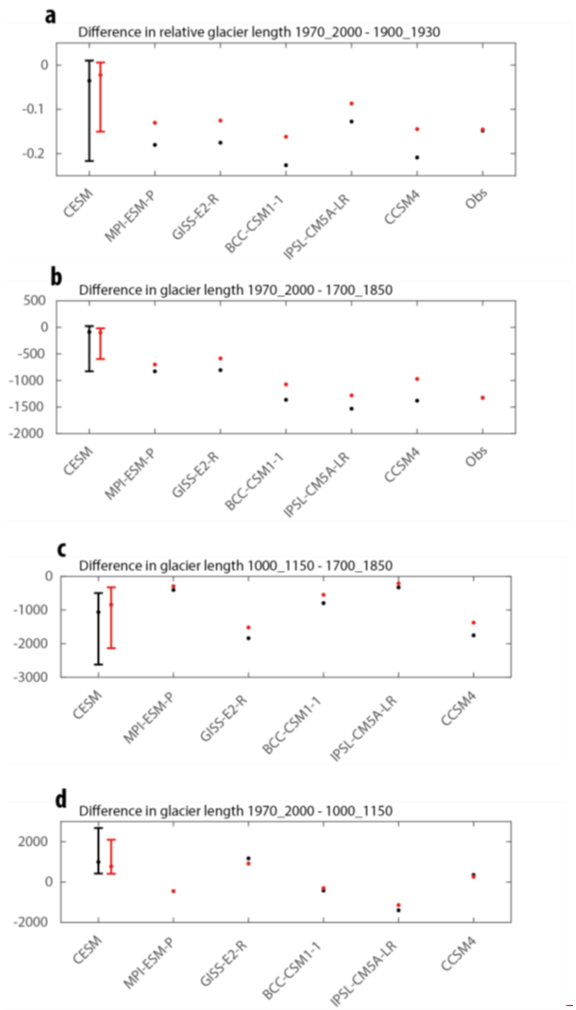


Figure 3. (a) Absolute and (b) relative length changes averaged over the 71 glaciers. The relative length is obtained by dividing the glacier changes by their length in 1950 in the compilation of Leclercq et al. (2014). The average for observations is performed over the available time series for each period, meaning that the number strongly decreases with time and, in particular, is very low before 1700. The reference period is 1901-1930 CE.


a
Difference in relative glacier length 1970_2000 - 1900_1930
0
-0.1
-0.2
CESM
MPI-ESM-P
GISS-E2-R
BCC-CSM1-1
IPSL-CM5A-LR
CCSM4
Obs
b
Difference in glacier length 1970_2000 - 1700_1850
500
0
-500
-1000
-1500
-2000
CESM
MPI-ESM-P
GISS-E2-R
BCC-CSM1-1
IPSL-CM5A-LR
CCSM4
Obs
c
Difference in glacier length 1000_1150 - 1700_1850
0
-1000
-2000
-3000
CESM
MPI-ESM-P
GISS-E2-R
BCC-CSM1-1
IPSL-CM5A-LR
CCSM4
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Difference in glacier length 1970_2000 - 1000_1150
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-2000
CESM
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GISS-E2-R
BCC-CSM1-1
IPSL-CM5A-LR
CCSM4

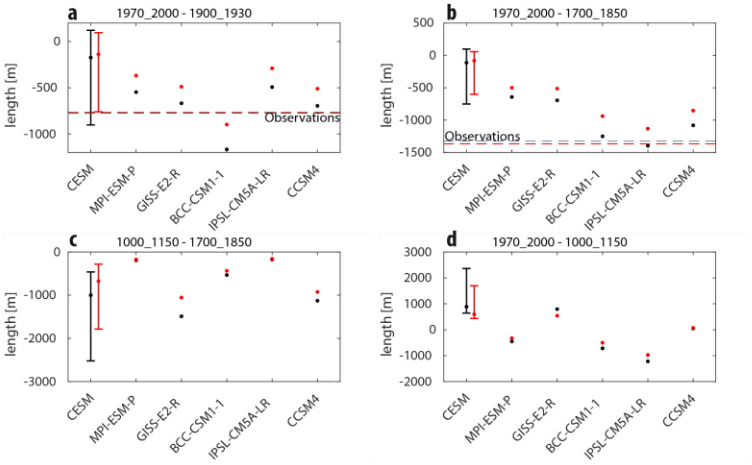


Figure 4. Mean (black) and median (red) of the difference in glacier length between a) 1970-2000 and 1900-1930; b) 1970-2000 and 1700-1850; c) 1000-1150 and 1700-1850; d) 1970-2000 and 1000-1150. On panels a and b, observations are given as a horizontal dashed line. No observation is available for panels c and d. For panel b, the average of model results is made only for the glaciers that have observations. For CESM, the bar gives the ensemble range.

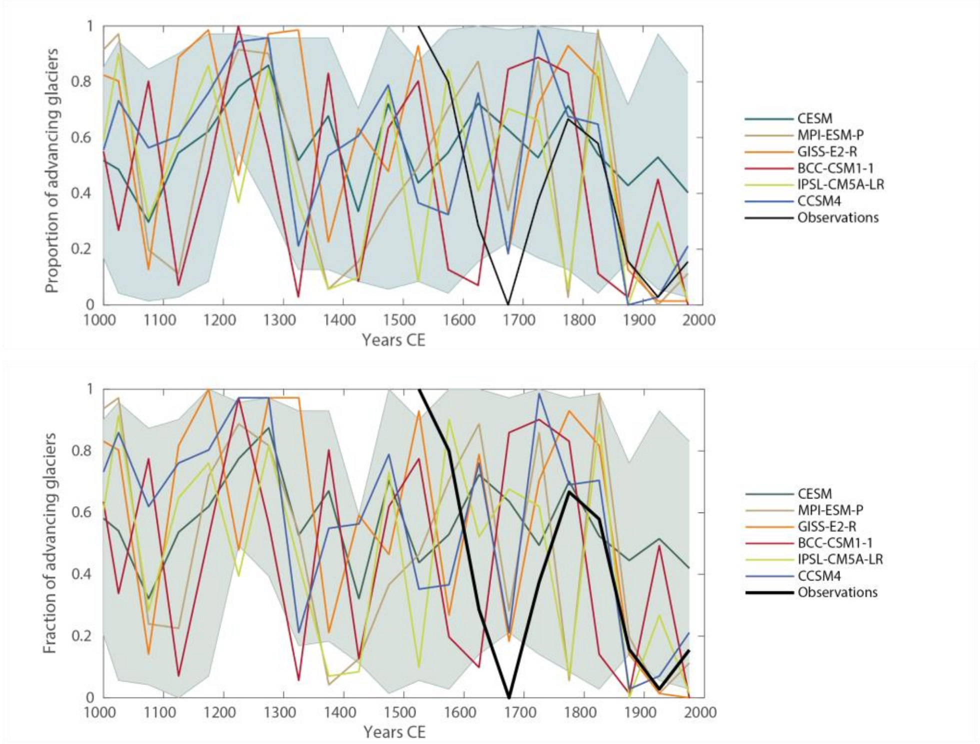
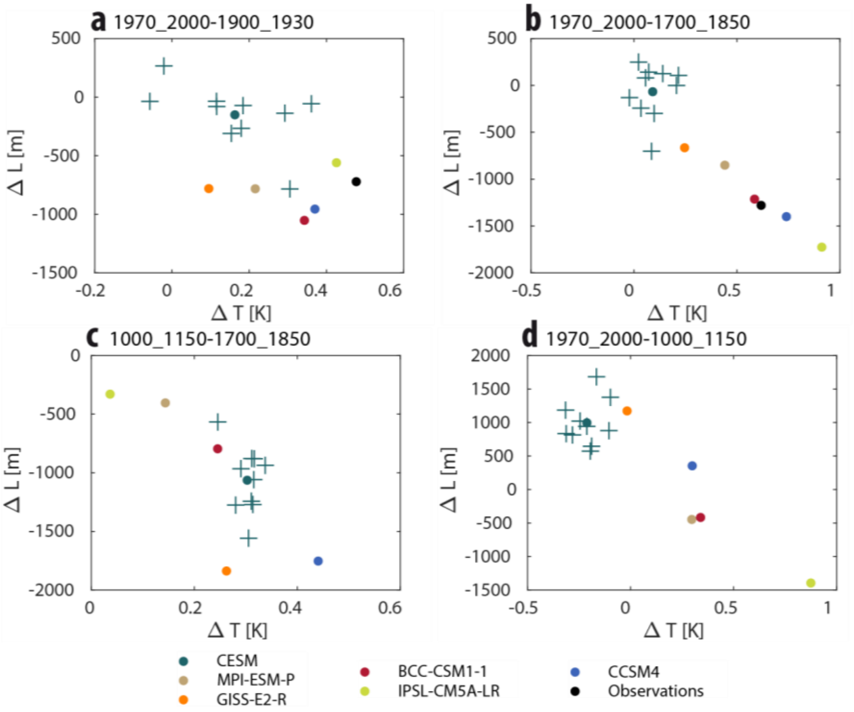


Figure 5. Proportion of glacier advances binned for 50 year intervals.


a 1970_2000-1900_1930
500
0
-500
-1000
-1500
-0.2
0
0.2
0.4
0.6
Δ L [m]
Δ T [K]
b 1970_2000-1700_1850
500
0
-500
-1000
-1500
-2000
-0.5
0
0.5
1
Δ L [m]
Δ T [K]
c 1000_1150-1700_1850
0
-500
-1000
-1500
-2000
0
0.2
0.4
0.6
Δ L [m]
Δ T [K]
d 1970_2000-1000_1150
2000
1500
1000
500
0
-500
-1000
-1500
-0.5
0
0.5
1
Δ L [m]
Δ T [K]
● CESM
● MPI-ESM-P
● GISS-E2-R
● BCC-CSM1-1
● IPSL-CM5A-LR
● CCSM4
● Observations

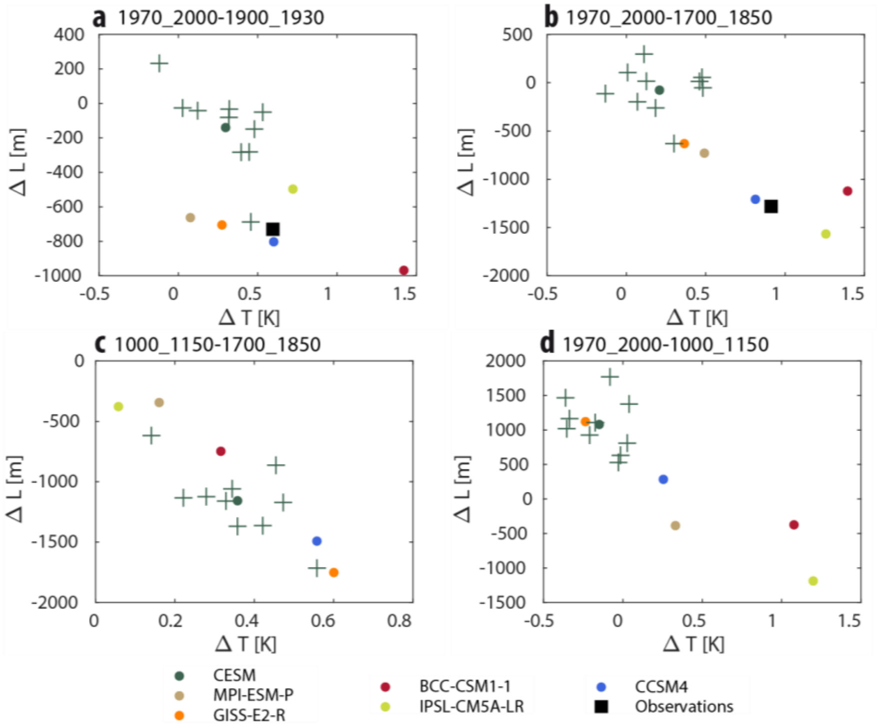
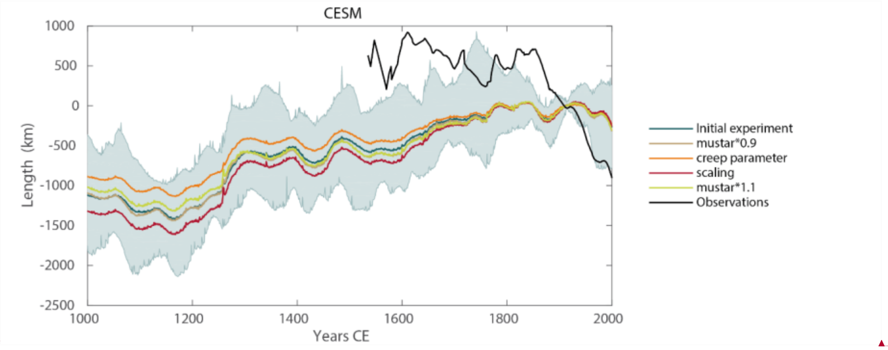


Figure 6. Glacier length changes as a function of summer temperature changes in the Alps ~~Summer temperature change as a function of glacier length~~ for the differences between a) 1970-2000 and 1900-1930; b) 1970-2000 and 1700-1850; c) 1000-1150 and 1700-1850; d) 1970-2000 and 1000-1150. For b, the average of model results is made only for the glaciers that have observations. The crosses represent the individual CESM ensemble members, the ensemble mean being represented by a dot of the same color.

Mis en forme : Couleur de police : Automatique



Mis en forme : Anglais (États-Unis)

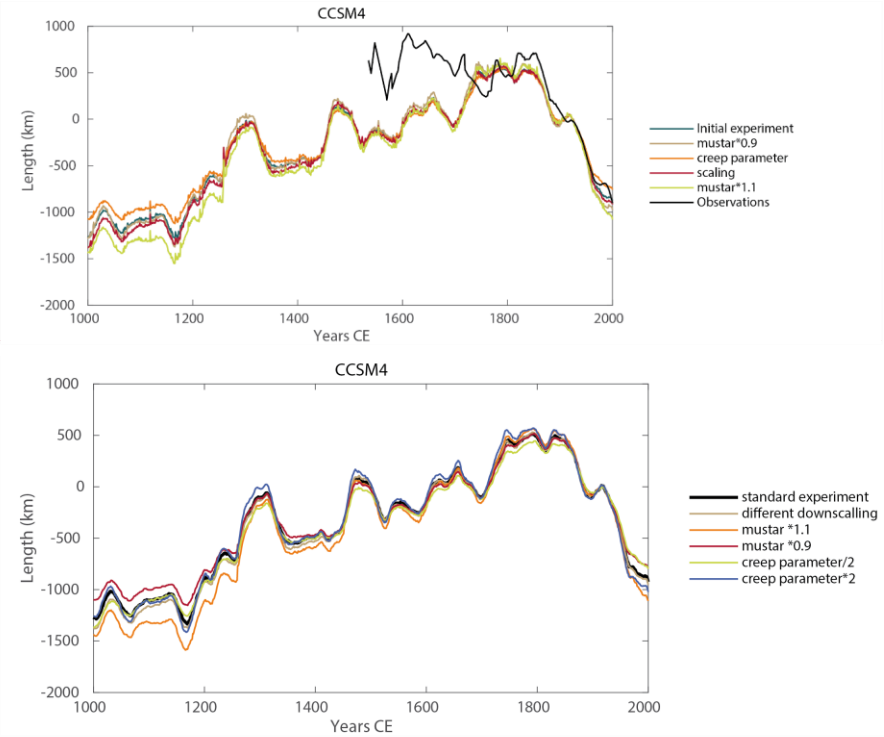


Figure 7. Length changes averaged over the 71 glaciers for the standard and sensitivity experiments using ~~a) CESM and b)~~ CCSM4 results. ~~For CESM, the ensemble range is given only for the standard experiment (mean plus and minus one standard deviation of the model ensemble as for Figure 3), while only the ensemble mean is provided for the sensitivity experiments.~~