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Climate of the Past Discussions

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

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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 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,

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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; Neukom et al., 2014; Moberg et al., 2015; PAGES2k-PMIP, 2015).

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 temperature and precipitation changes over the glacier, as well as of the glacier dynamics and thus local geometry (Oerlemans, 2001; Huss et al., 2008; Roe, 2011). Furthermore, glaciers integrate forcing over timescales ranging from a few years to several decades or even centuries. 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).

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 (Jomelli et al., 2011; Leclercq et al., 2012; Luthi, 2014; Malone et al., 2015; Sagredo et al., 2017; Zechetto 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 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 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 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). 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). 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.

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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 (Otto-Bliesner et al., 2009; Taylor et al., 2012). 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 past1000 (years 851-1850) and the historical (years 1851-2005) simulations but the jump is relatively small 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 simulation 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):

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

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 is equal to -1°C in OGGM as melting may occur some days even though the monthly mean is below 0°C. μ^* is temperature sensitivity parameter and ε a residual bias. $\mu^*$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. 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, 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 CMIP5 protocol. However, as sensitivity tests have shown that the first century is influenced by the choice of initial conditions for the glaciers, 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 Fluctuations of Glaciers (www.wgms.ch, WGMS 2017). The modern observations can be complemented by historical sources including painting, drawing and early photographs as well as written documents (Grove, 2004; Nussbaumer and Zumbühl, 2012). 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; Wiles et al., 2011; Leroy et al., 2015).

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, 7 to 1700 and the longest record starts in 1535 (Unterer Grindelwald), allowing for each of them a quantitative comparison with model results at centennial timescales. The complete list of glaciers is provided in the supplementary material. Longer records are also available for many glaciers but

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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

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), it is 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).

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 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 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 glaciers on Figure 2. 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~~ 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 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 range of the ensemble (Fig. 4a). Consequently, although the magnitude of the changes ~~vary~~ 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 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 (Fig. 4c), when the glacier extent was close to its minimum in nearly all the simulations, and the years 1700-1850 confirms the differences deduced qualitatively from Fig. 3. Some models have a large positive 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 ~~where~~ smaller during the period 1000-1150 in the simulations driven by CESM and GISS outputs. It is difficult to estimate from observations when glaciers where smaller than presently as the evidence may still be buried under the ice (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 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.

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 (Luthi et al., 2014; Leroy 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.

The early 15th century that stands out as a minimum for glacier advances in many models is also a period with a relative minimum in glacier length but the simulated temperature are not very different from earlier or later period and in particular

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are generally lower than in the beginning of the millennium. This clearly illustrates that glaciers have a long response timescales. The simulated glacier retreats are partly due to the relatively mild conditions in the late 15th century but also to recovery from the large advances in the 13th and 14th century.

The association between summer temperature and glacier changes is more direct 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 ~~model~~ 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. 6). The link is a bit less clear when focussed on the 20th century, because the investigated period is shorter. Nevertheless, this confirms the 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 experiment, the creep parameter has been multiplied by a factor two for all the glaciers, applying then a value of $4.8\ 10^{-24}\ s^{-1}\ Pa^{-3}$. 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 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 in Fig. 7. Similar results have been obtained for the other ones. The results for CESM ensemble 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, 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 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 models over the past millennium, confirming using a new type of data the 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, 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 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 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.

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 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. 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. 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.

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 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)

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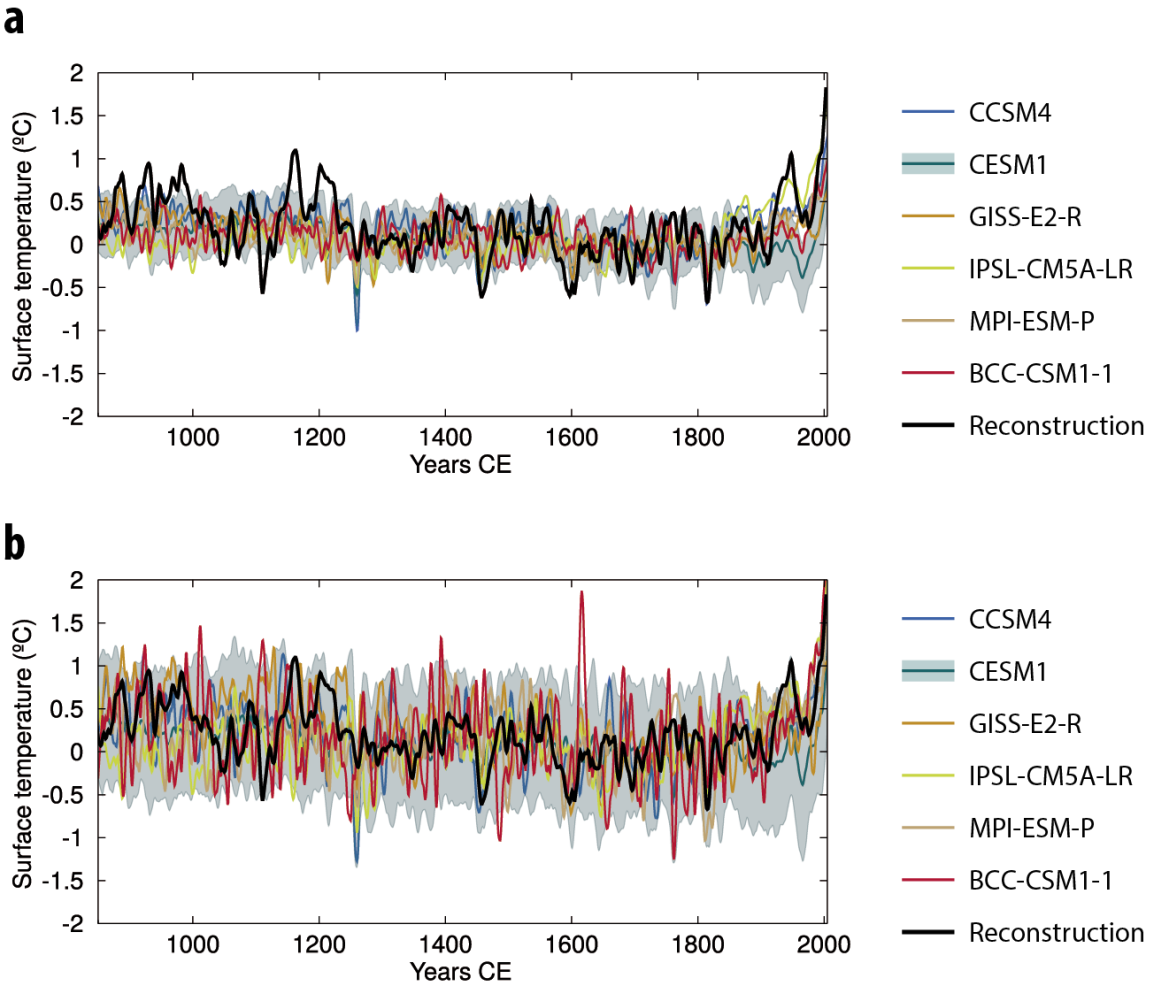

Figure 1. Summer temperature overaged over a) Europe and b) the Alpine region (defined here as the area between 45 and 48°N and between 6 and 13°E) in the reconstruction of Luterbacher et al. (2016) and as simulated by climate models over the past millennium. The shaded area represents the mean plus 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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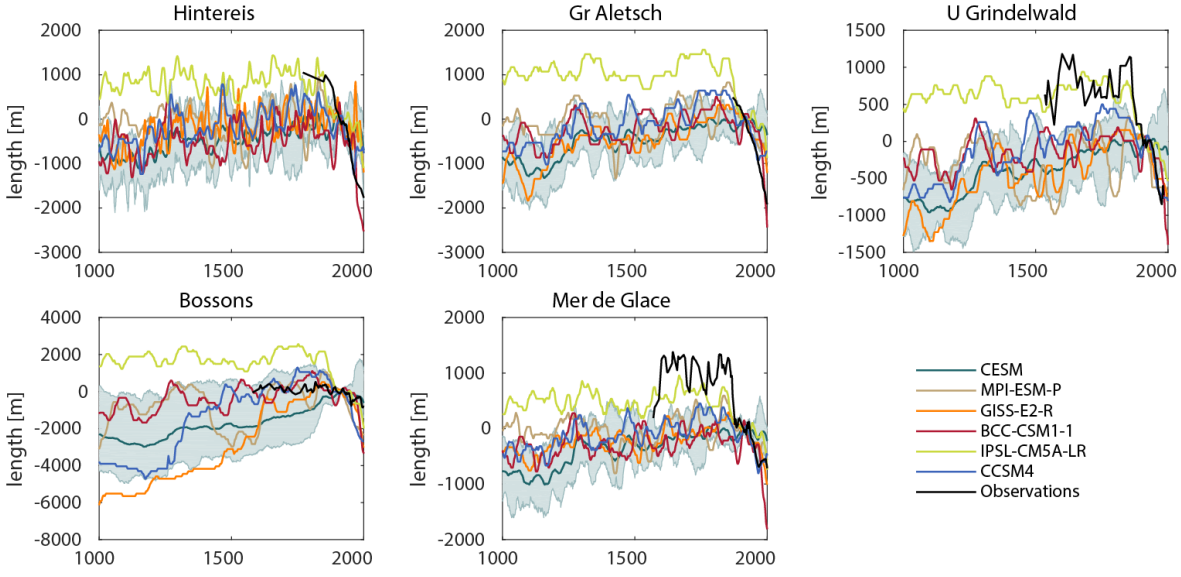

Figure 2. Observed and simulated length for five selected glaciers in the Alps. The shaded area represents the range of the ensemble of simulations driven by CESM outputs. The reference period is the years 1901-1930.

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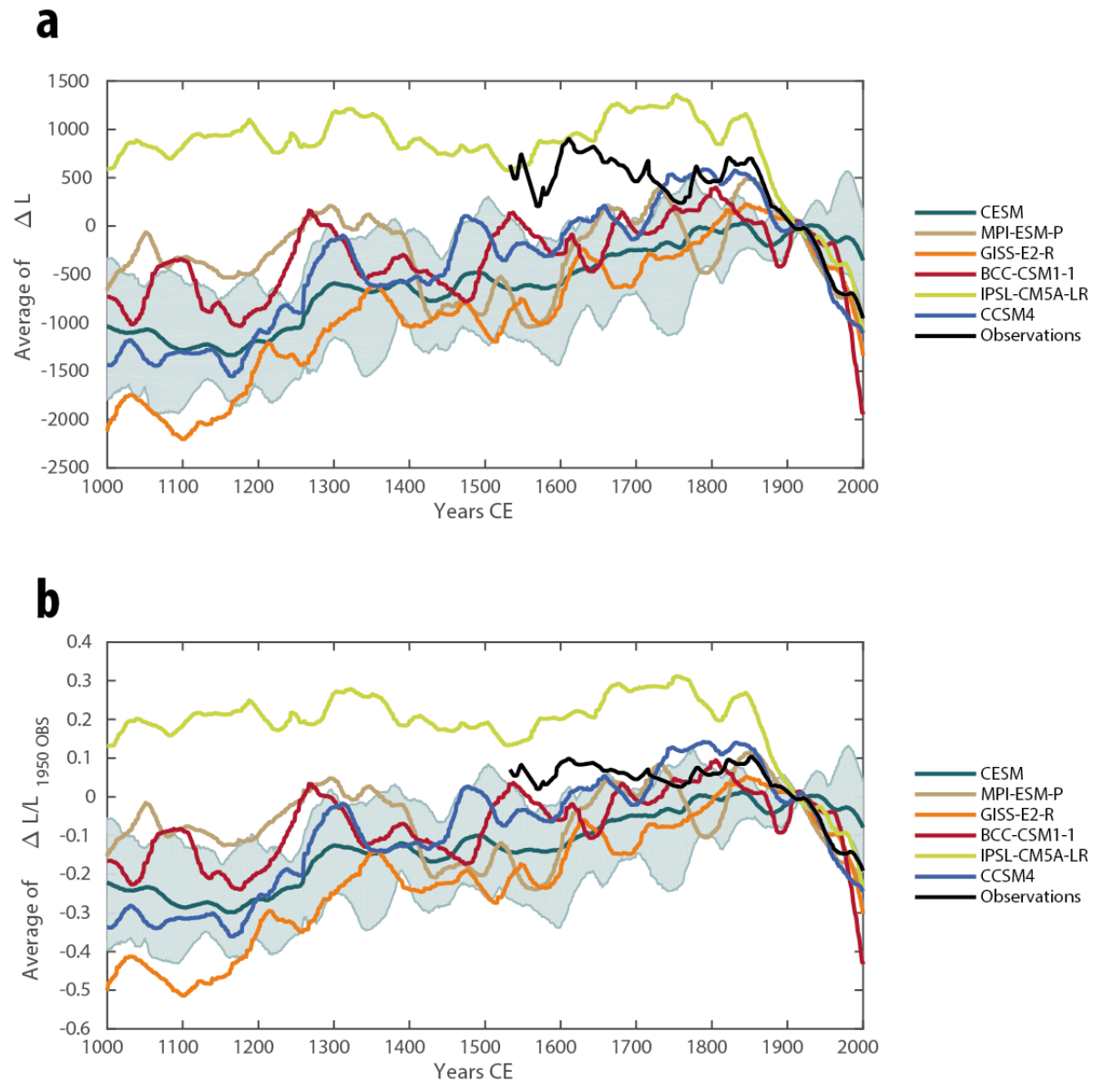

Figure 3. (a) Absolute and (b) relative length changes averaged over the 71 glaciers. The relative length is obtained by dividing the glacier changes by their length in 1950 in the compilation of Leclercq et al. (2014). The average for observations is performed over the available time series for each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

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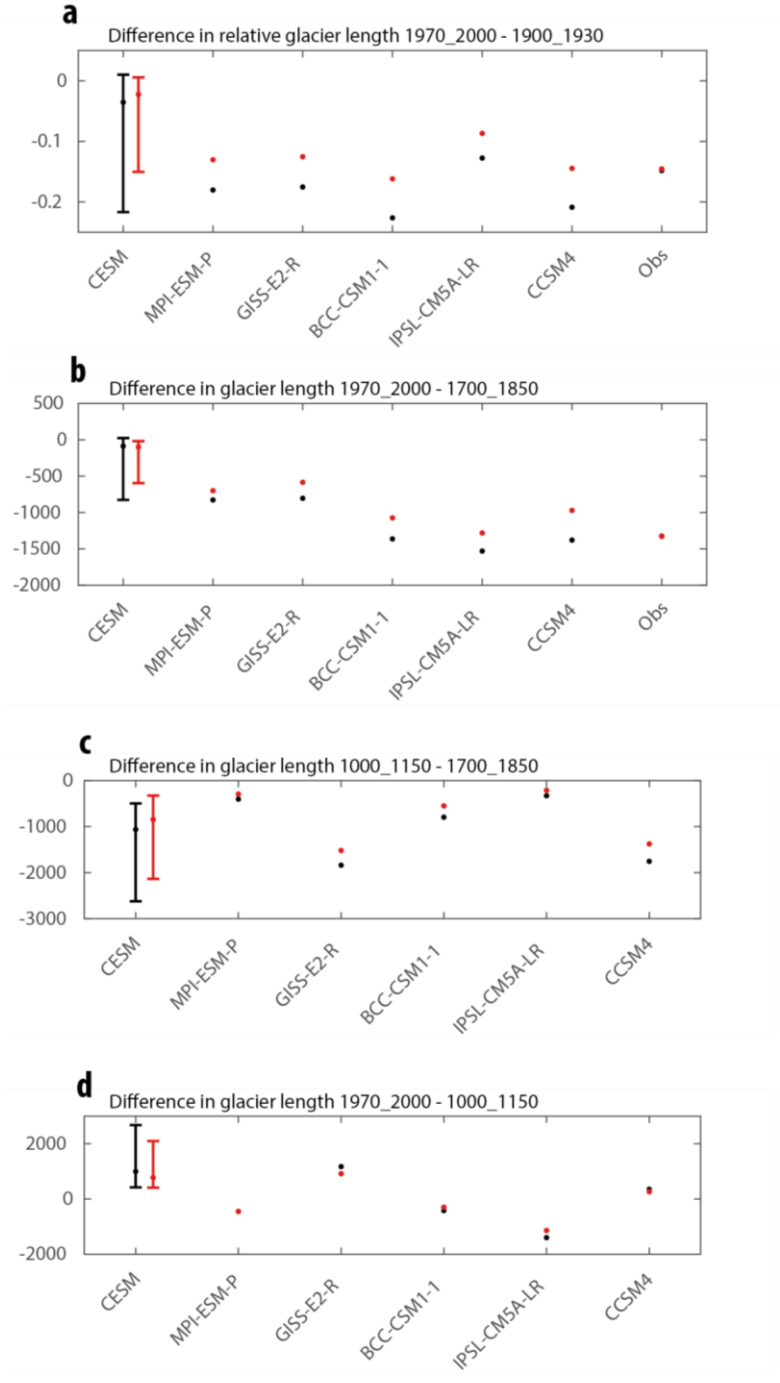

Figure 4. Mean (black) and median (red) of the difference in glacier length between a) 1970-2000 and 1900-1930; b) 1970-2000 and 1700-1850; c) 1000-1150 and 1700-1850; d) 1970-2000 and 1000-1150. No observation is available for panels c and d. For panel b, the average of model results is made only for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

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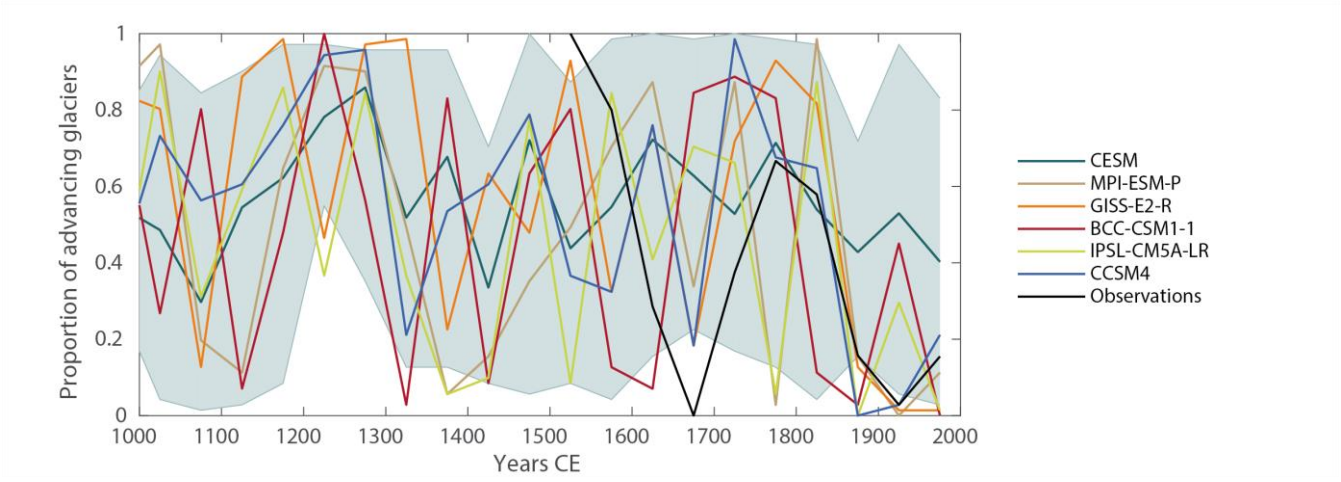

Figure 5. Proportion of glacier advances binned for 50 year intervals.

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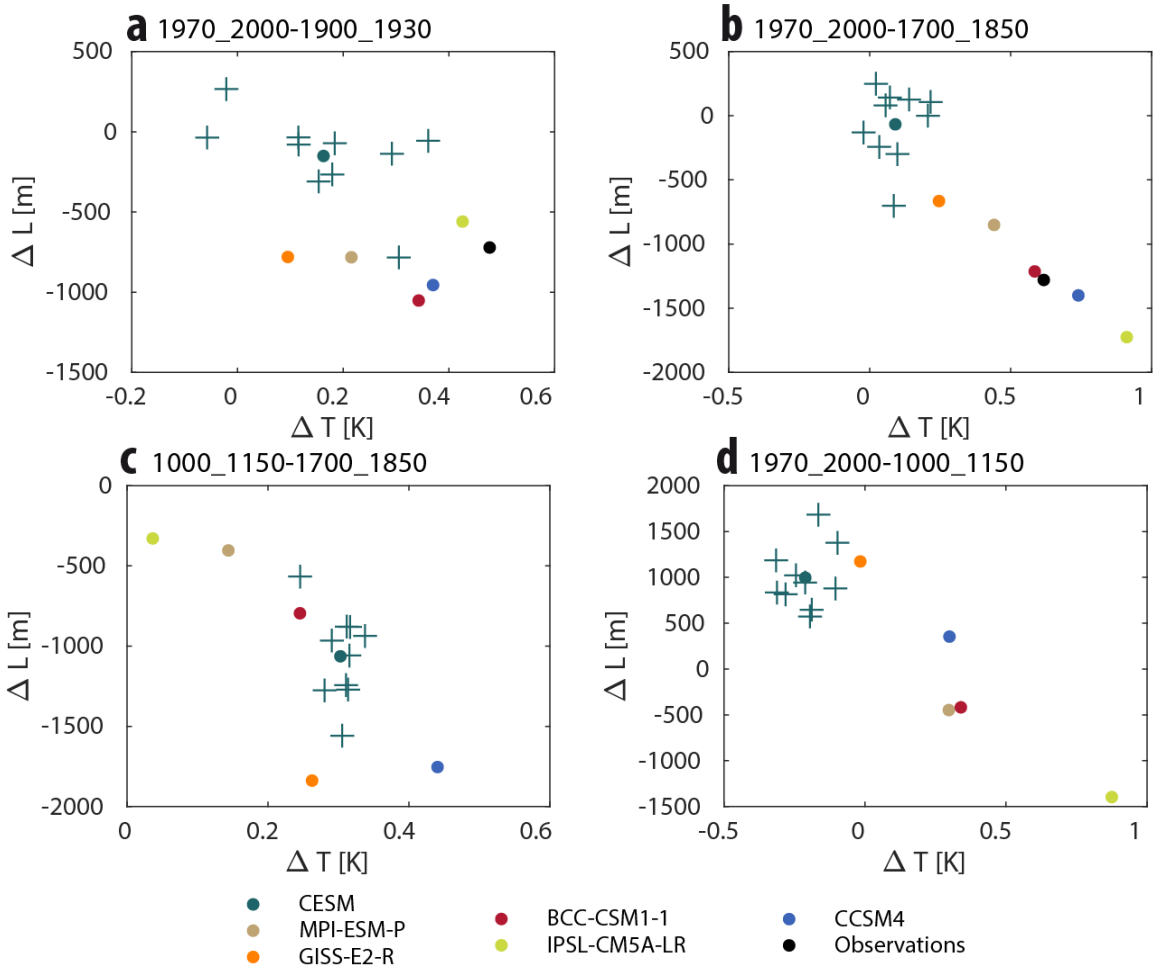

Figure 6. Summer temperature change as a function of glacier length for the differences between a) 1970-2000 and 1900-1930; b) 1970-2000 and 1700-1850; c) 1000-1150 and 1700-1850; d) 1970-2000 and 1000-1150. For b, the average of model results is made only for the glaciers that have observations. The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

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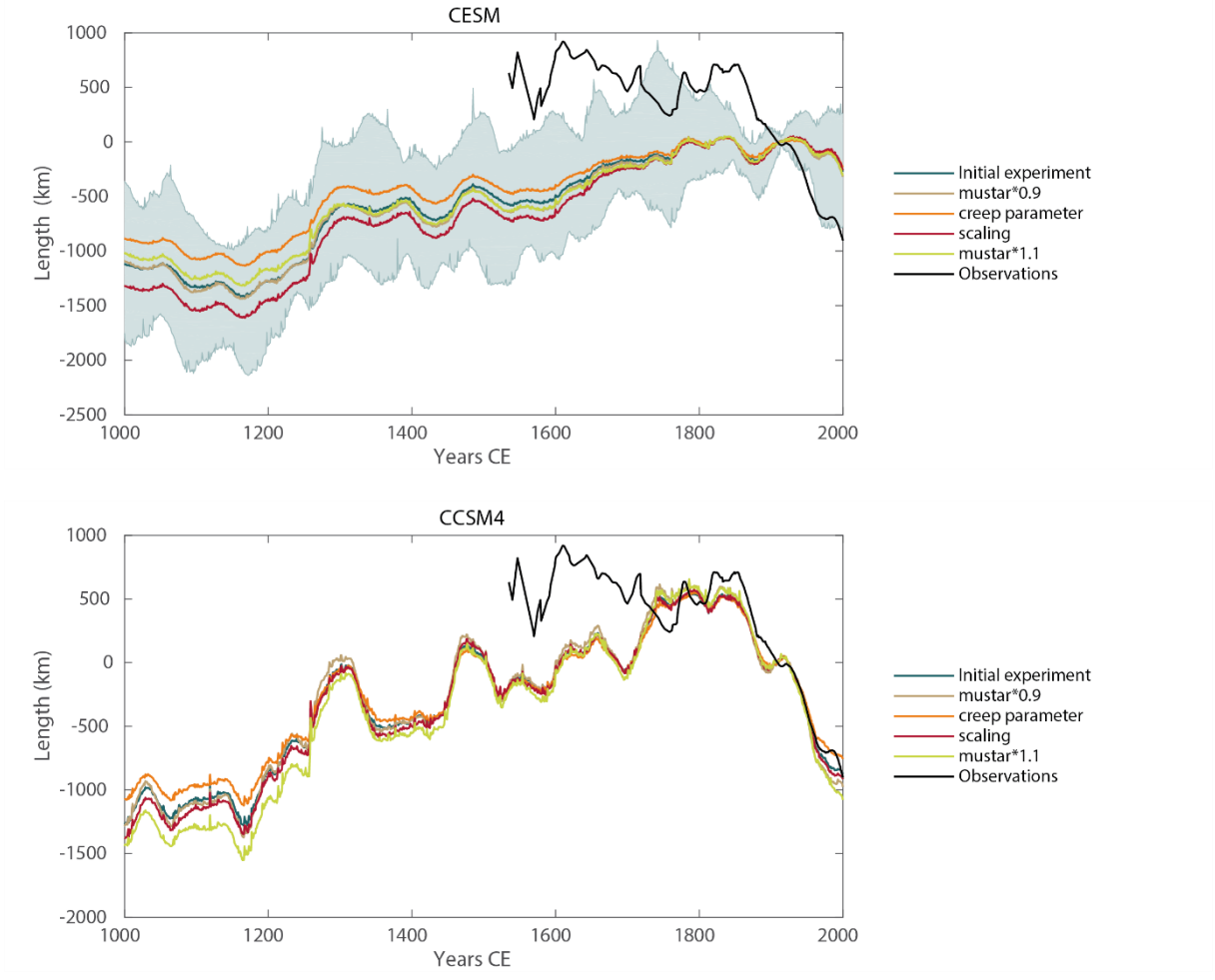

Figure 7. Length changes averaged over the 71 glaciers for the standard and sensitivity experiments using a) CESM and b) CCSM4 results. For CESM, the ensemble range is given only for the standard experiment (mean plus and minus one standard deviation of the model ensemble as for Figure 3), while only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