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Modelling regional glacier length changes over the last millennium using the Open Global Glacier Model

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Abstract. A large majority of the direct observational record for glacier changes falls within the post-industrial period, associated with global glacier retreat. Given this availability of data, and significant focus in contemporary glacier modelling falling on post-industrial retreat, glacier models are typically calibrated using - and validated with - only observations from points where glaciers were considerably out of equilibrium. In order to develop a broader picture of the skill of one glacier model in active development - the Open Global Glacier Model (OGGM) - we model glaciers for extended historical timescales of 850-2004 CE using a selection of 6 climate model outputs, including recent post-industrial history. We select glaciers for which long term glacier length observations are available, in order to compare these observations with the model results, and we find glaciers for this purpose in almost all glacierised regions globally. In many regions, the modelled glacier changes are consistent with observations, with recent retreat often as rapid as - or sometimes more rapid than - modelled retreats. We also model this set of glaciers using modified climate timeseries from each of the 6 climate models to keep temperature or precipitation constant, testing the impact of each individually. Temperature typically explains considerably more variance in glacier lengths than precipitation, but results suggest that the interaction between the two is also significant within OGGM and neither can be seen as a simple proxy for glacier length changes. Overall, with the vast majority of glaciers successfully modelled, and recent observational trends in many regions reproduced by the model running over a considerably larger timescale than it is calibrated for, prospects are good for more widespread use of OGGM for timescales extending to the pre-industrial, where glaciers are typically larger and experience less rapid (and less globally consistent) geometry changes.

1 Introduction

Robust modelling of the evolution of glacier mass and geometry on regional and global scales is of critical importance for understanding the components of historical sea level rise and for predicting one of the potential largest contributors to sea level rise in coming centuries (Church et al., 2013). Moreover, glacier geometry changes are themselves an indicator of local (for individual glaciers) and regional (for glaciers considered across a wider area) climate changes (Oerlemans, 1986, 2017). Direct observations of glacier geometry are relatively sparse, however (Zemp et al., 2015; Cogley, 2009), and it is only through recent aerial (WGMS (World Glacier Monitoring Service) and NSIDC (National Snow and Ice Data Center), 1989) and satellite mapping (RGI Consortium, 2017) that fairly comprehensive inventories of glaciers across all of the world's glacierised regions have become available, cataloguing upwards of 200,000 glaciers (though even this is likely a significant underestimate

https://doi.org/10.5194/tc-2019-275
Preprint. Discussion started: 16 December 2019

(Parkes and Marzeion, 2018)). Investigating the past and future state of glaciers on large scales therefore necessitates the use of glacier models that can accurately forecast or hindcast glacier evolution with relatively little historical observational data for calibration, and without a prohibitive computational cost. This is one of the primary goals of the Open Global Glacier Model (OGGM) (OGGM e.V., 2019; Maussion et al., 2019) project.

High quality, globally comprehensive datasets of both climate and glacier geometry are only available for the relatively recent past, limiting the period available for either model calibration or comparison of models with observational data. OGGM by default calibrates the glacier sensitivity to local temperature based on CRU data (Jones and Harris, 2013) that begins in 1901, and uses RGI glacier outlines which are typically from around the start of the 21st century (RGI Consortium, 2017). In many regions, glaciers are already experiencing significant retreat by the beginning of the 20th century (Zemp et al., 2015), and calibrating glacier models for time periods when glaciers are far from equilibrium brings additional challenges. With much of the focus of glacier modelling on post-industrial retreat and future predictions, a longer term historical view of glacier changes provides valuable context; for glacier models developed using data primarily collected in the 20th and 21st centuries, during periods of glacier retreat, it is important that these models are examined over time periods where more stable glacier geometries were expected. In this study, we expect that the last millennium provides smaller - and less globally consistent - temperature trends than the post-industrial record alone (Neukom et al., 2019; PAGES 2k Consortium, 2013, 2017). While there are discernible large scale temperature trends within the last millennium (notably the Medieval Warm Period - c. 10th to 13th centuries CE - and Little Ice Age - c. 16th to 19th centuries CE), none have either the spatio-temporal consistency or the magnitude of recent post-industrial warming. This allows the glacier model to be tested over a period where glaciers are expected to remain more stable, potentially with both advances and retreats at more moderate rates than have been recently observed. Due to the limits on the observational data for comparison, we cannot compare model results with an accurate representation of pre-industrial relative glacier lengths, so a greater focus is placed on whether (and when) the modelled glaciers transition from more stable pre-industrial lengths to expected recent retreat than on pre-industrial trends.

Another issue with large-scale glacier modelling is the highly spatially inhomogenous nature of historical records of glacier change. Observations are typically concentrated in more accessible regions, rather than distributed evenly by glacierised area, and this is compounded in the longest-term observations. This naturally biases glacier model development towards representation of certain regions - most notably central Europe - which do not contain a large proportion of global glacier mass, and which are not necessarily representative of glaciers in larger regions. For this reason it is important to assess the performance of glacier models on a per-region basis, and to determine how well models can reconstruct observed changes in the best-observed regions compared less well-observed regions.

From another angle, as glaciers aggregate changes in local climate, modelling of glaciers under a modelled or reconstructed climate can be considered a test of the climate model/reconstruction's skill at reproducing the variables which drive glacier models (in the case of OGGM, temperature and solid precipitation). Usage of glacier models for this purpose is dependent on both the level of confidence in the glacier model's skill and the available observations to compare with modelled glacier states, but there is potential for longer-term historical glacier modelling to provide a link between proxies for glacier extent (such as

https://doi.org/10.5194/tc-2019-275
Preprint. Discussion started: 16 December 2019

morraine positions and presence/absence of trees, or indicators of meltwater presence in different time periods) and models or reconstructions of past climate (e.g. Daigle and Kaufman (2009)).

In this paper, we use OGGM to model a selection of glaciers for which long-term length observations exist (Leclercq et al., 2014) in almost all major glacierised regions over the last millennium, and compare modelled length changes to observations. OGGM is driven by the outputs from a number of climate models, in order to compare the differences between these models to the variability over time in OGGM output driven by any single climate model. This approach has already been applied to European glaciers (Goosse et al., 2018) and the application to many glacierised regions adds valuable understanding of model behaviour and glacier dynamics in different climate conditions - including for future applications modelling entire global glacier inventories - and allows comparison of differences between models and differences between regions. We also use modified climate variable timeseries with constant precipitation or temperature (including only high-frequency variation) for each of the climate models, as a sensitivity experiment to determine the relative contribution of each variable when any trend from the other is removed.

2 Methods and Data

The Open Global Glacier Model (OGGM) version 1.1 (Maussion et al., 2019), updated to the most recent code version as of 2019-03-28, is used for modelling the glaciers in this study. OGGM is an open source model for glacier dynamics, which accounts for glacier geometry and ice dynamics. Glacier mass balance is calculated using a temperature-indexed degree-month model, generating monthly accumulation or melt at the specific elevation of each point on the glacier. Full details are given in the paper that describes the model, and further background on the mass balance calculation is available in the precursor to OGGM described in Marzeion 2012 (Marzeion et al., 2012).

Initial glacier outlines and topography are taken from the Randolph Glacier Inventory (RGI) (RGI Consortium, 2017) and several digital elevation models (SRTM (CGIAR-CSI, 2019), GIMP (NSIDC, 2019), Viewfinder Panoramas DEM3 (de Ferranti, 2019)) respectively, using OGGM's 'level 3' default preprocessing. This level of preprocessing contains the outputs for all steps of the preparation of initial glacier state using default parameters, so the runs performed in this study can focus exclusively on running the dynamic glacier model in response to varying climate datasets with consistent parameters and initial glacier geometry.

Our OGGM runs use input from 6 different climate models, each covering a period from 850 to 2005 CE. These models are CESM, IPSL, GISS, BCC-CSM, CCSM4, and MPI - using simulations under the Past Model Intercomparison Project (PMIP3) and the Coupled Model Intercomparison Project (CMIP5) protocols (Schmidt et al., 2011; Taylor et al., 2012; PAGES 2k-PMIP3 group, 2015) - with details exactly as listed in Goosse et al. (2018) table 1 and section 2.1, with the exception that only a single simulations from CESM is used. OGGM results are produced for the years 851-2004 CE, due to the requirements for clipping the data to match hydrological years. The primary runs use this data as provided, while a secondary set of runs for each climate model, referred to as 'constant temperature'/'constant precipitation' respectively, have the temperature/precipitation in each year randomly selected from a year in the 1400-1450 (inclusive) window from each model's output,

https://doi.org/10.5194/tc-2019-275
Preprint. Discussion started: 16 December 2019

with the precipitation/temperature respectively the same as in the primary runs. The randomised 51-year window provides a temperature/precipitation time series that represents a constant long-term climate while preserving some degree of interannual variation, so that the impact of a lack of long-term trend in the temperature/precipitation values can be examined. The period of 1400-1450 is chosen for centrality within the dataset, and because it falls neither within the Medieval Warm Period nor the Little Ice Age. For all runs, a 300-year spinup using annual climate data selected randomly from a 51-year window of 875-925 CE from the same model is performed prior to the run, to allow the glacier to develop from the preprocessed glacier geometry (based on RGI data and therefore representative of the year of the observation used) to a more realistic geometry for the climate near the start of the model run.

In order to compare modelled length changes with a set of observations which covers most RGI regions, the glaciers we model are those featured in a 2014 dataset of observed glacier length fluctuations compiled by Leclercq et al (Leclercq et al., 2014). The identification of glaciers from the Leclercq dataset with glaciers in the RGI - necessary for modelling in OGGM - is non-trivial, and is described below. Length change observations are arguably the simplest metric of glacier geometry change as they can be determined using only snapshots of terminus location, which is why this observational dataset goes further back in time for many glaciers than reliable observations of glacier area or volume. The dataset shows certain biases which impact how well we can expect the glaciers to be globally or regionally representative samples. Firstly, the number of glaciers observed per region is not representative of either total glacier number or total glacier area (see Table 1 for regional totals used). Most notably, the Central Europe region has the largest number of observations, despite containing much less total glacier area than many other regions. This precludes the production of meaningful global figures in this paper. Secondly, larger glaciers are heavily over-represented in the Leclercq dataset compared to comprehensive modern inventories like the RGI (and larger glaciers may also still be overrepresented in the RGI (Parkes and Marzeion, 2018)). This means that the response time of the Leclercq dataset glaciers is expected to be longer than for glaciers in each region as a whole. The comparison of model results and observations is not affected by this directly, as all comparisons are like-for-like on specific glaciers or sets of glaciers, but it does mean that the changes shown are likely a) slower and b) smaller in relative magnitude compared to the true regional averages, which contain many smaller glaciers that typically have faster and proportionally greater responses to changes in local climate.

The length change timeseries in the Leclercq dataset vary considerably in the number of years covered and in the frequency of observations; within any given region, the number of available data points can vary from year to year, so it is important to choose a representation of mean regional glacier length that can handle this. All possible solutions have positives and negatives, but we opt to normalise each glacier's length to its 1950 length (or interpolated 1950 length) as this year is covered by observations for every glacier in the Leclercq dataset. For each modelled (or observed) glacier length timeseries, the normalised length timeseries is given by the length in each year divided by the length in 1950. Regional mean glacier length is calculated as the mean of this normalised length across all glaciers which have observations covering a given year. This reduces the 'spikes' in mean regional length which arise from changes in the number of glaciers with measurements in a particular year, especially when the glaciers joining or leaving the mean are far from the mean absolute glacier length, though we do still see spikes in the Leclercq dataset averages as artefacts of the sampling, particularly in the earlier parts of the regional timeseries where

https://doi.org/10.5194/tc-2019-275
Preprint. Discussion started: 16 December 2019

the glacier number contributing to the average changes while the total number of glaciers is small. Based on this decision, all regional means for the OGGM output for each climate model are represented in the same way, normalised to the mean length in 1950 for each climate model. This removes the ability to immediately judge differences in mean regional absolute glacier length between models - indicative of the relative biases of the model overall, and of the ability of the bias correction technique to remove those biases - but makes comparing periods of advance and retreat between models much easier.

Glaciers from the Leclercq dataset are identified with the glaciers in the RGI in two steps. First an attempt is made to find a positive match in the RGI for the glacier described in the Leclercq dataset, according to an objective standard, and if this fails, an attempt is made to find a nearby glacier which may not be confidently identified as the glacier described in the Leclercq dataset, but can be used as a 'best effort' for the purpose of comparing local glacier changes. These two types of identification are kept distinct, and labelled as such in the glacier list. To find positive matches, the criteria are the following: 1) the (lat, lon) pair given in the Leclercq data must either lie within the outline of an RGI glacier, or within rounding distance for the (lat, lon) values (which are given to 2 decimal places); and 2) the area given in the Leclercq data must be within a factor of 2 of the RGI glacier. In cases where the (lat, lon) pair given is exactly on the border between connected glaciers, or within rounding distance for more than one glacier but within the outline of neither, and both glaciers satisfy the 2nd condition, one glacier is selected but moved to the 'best effort' class (though occasionally this will not be necessary if one of the RGI glaciers can be uniquely identified with a different Leclercq glacier, as the other can then be positively identified as the correct Leclercq glacier). The 1st criterion is not applied as strictly in certain cases where the (lat, lon) pair is close to a larger glacier and there are no other glaciers nearby, particularly when the (lat, lon) location is clearly downstream of an RGI glacier's tongue as this represents a rapid tongue retreat between the time of the Leclercq measurement and the time of the RGI measurement. The 'best effort' criteria are much looser, simply selecting the most size-appropriate glacier in the local group of glaciers (but not any RGI glacier which is positively identified as a different Leclercq glacier). If there are either no local RGI glaciers or the given size of the Leclercq glacier is vastly different to that of any local RGI glaciers, no 'best effort' glacier is identified and the glacier status is given as 'not found'. For the 471 glaciers in the Leclercq dataset this process gives 291 positive matches, 121 best-effort matches, 38 not found, and the remaining 21 Antarctic glaciers unprocessed due to lack of CRU data for calibrating sensitivity in surface mass balance calibrations.

All 412 of the glaciers matched between the Leclercq dataset and the RGI are modelled, but we cut down the results to exclude marine- and lake-terminating glaciers. Before any modelling concerns, the loss of ice at the glacier terminus through calving makes the terminus location (and therefore glacier length) a less useful indicator of glacier geometry changes, as the terminus can remain in a similar location through considerable thinning or thickening of the glacier while the calving flux changes. In the context of OGGM, the default settings used here do not include a parameterisation of calving, which has a large impact on glacier geometry. OGGM does allow for a parameterisation of calving flux (Recinos et al., 2018), but this still relies on a fixed location of the calving front that enforces a physically unrealistic calving-front thinning followed by a transition to a non-calving regime if the glacier is expected to retreat, so it does not improve our ability to examine the evolution of glacier geometry through the lens of accurately modelled length changes. 73 glaciers are excluded from the regional averages due to

https://doi.org/10.5194/tc-2019-275
Preprint. Discussion started: 16 December 2019

being marine- or lake-terminating, leaving 339 from which regional averages are determined. The numbers excluded per region are shown in Table 1.

3 Results

Figure 1 shows the regional mean length results for the years 1000-2004 CE for the runs using temperature and precipitation data as provided by each of the 6 climate models. The model itself runs using this data from 851-2004, but we limit our graphs to 1000 CE onwards in order to limit the impact of a continued adjustment towards equilibrium even after the 300 year spinup for certain model/region combinations, which is a modelling issue and not a response to actual climate trends. Table 1 shows the number of glaciers per region contributing to the mean for each of the climate models, with glaciers removed if they are not land-terminating or if there are modelling errors using at least one of the 6 climate models. Figure 2 shows the same timeseries as Fig. 1, but restricted to 1800-2004 CE to better show the comparison between the model results and the bulk of Leclercq length change observations.

The results vary considerably between regions and between climate models within each region, but the most consistent trend is a majority of regions demonstrating some form of discernible post-industrial retreat for a majority of climate models. This is reflected by the Leclercq observations also demonstrating post-industrial retreat in a majority of regions, with the observations typically showing a relative retreat that is similar to the upper end of modelled retreats. There are 7 regions where the observed retreat is within the range of modelled retreat: Alaska, Western Canada/US, Greenland Periphery, Scandinavia, Central Europe, Caucasus/Middle East, and Central Asia, though in some cases the observed retreat is at certain points slightly steeper than the range of modelled retreats. In North Asia, Low Latitudes, and Southern Andes, we see trends of retreat over the 20th century in all models and in the Leclercq observations, but all of the models underestimate the retreat shown in the observations. Amongst the other regions, there are those where the modelled lengths are just too inconsistent to draw conclusions on where the observations sit within the modelled range (e.g. South Asia West), those where the observations show distinct features which are not present in the modelled trends (e.g. South Asia East), and those where there is neither consistency between models nor between the observations and any modelled lengths (e.g. New Zealand). However, it is difficult to find much consistency between regions where the observations and modelled lengths match poorly as the features appear specific to each region.

While the use of normalised glacier lengths removes the ability to tell which models result in longer or shorter glaciers at the end of the model run, and how these compare to observed lengths, it does allow the differences in responses to climate change trends between models to be seen more clearly. When the model results are highly stratified, such as in Central Europe, Southern Andes, or Caucasus/Middle East, this indicates that the differences between the results from each climate model can be attributed to significant differences in the climate variables for each model. In many cases, the stratification is the result of varying start years and severity of recent retreat. Results using the CESM and GISS models often have lower pre-industrial relative glacier length relative to 1950, indicating smaller and/or later starting post-industrial glacier retreat, while IPSL and BCC-CSM have high pre-industrial length relative to 1950, and show more pronounced and/or earlier-starting retreat; given the

https://doi.org/10.5194/tc-2019-275
Preprint. Discussion started: 16 December 2019

many regions where the observed retreat is at the upper end of the range of modelled retreats or even exceeds this range, IPSL-driven and BCC-CSM-driven lengths are more often a better match for the observations. As these differences are common between a number of regions, it indicates differences between the climate model data on scales greater than that of individual glacierised regions.

In order to determine the significance of the apparent retreat in the last ∼150 years for many model runs, a 'split regression' is performed for each climate model in each region. For each year from 901 to 1954 (we remove the first and last 50 years of the timeseries to avoid looking for trends in timeseries which are small compared to the expected response times of glaciers), we split the model output into a section up to and including that year and a section after that year, and perform a simple linear regression on each part. The 'best' split - that which best represents the timeseries in two linear trends - is chosen by maximising the summed r^2 values for the two sections. These best splits are shown in Fig. 3, and demonstrate that according to an objective standard for determining the separation of trends there is in many cases a clear post-industrial retreat. In 6 regions - Western Canada/US, Greenland Periphery, Central Europe, Low Latitudes, Southern Andes, and New Zealand - the runs for all 6 climate models show a distinction between pronounced recent retreat and a modest pre-industrial advance. In a further 7 regions - Alaska, Iceland, Svalbard, Scandinavia, North Asia, Caucasus/Middle East, and South East Asia - multiple climate models show a distinction between pronounced recent retreat and a pre-industrial trend (though in these cases the pre-industrial trend varies from moderate advance to moderate retreat). While it is not necessarily useful to consider the year of transition between the two regressions as the year there is a point of inflection in the glacier length, due to the restrictions imposed by separating into just two linear regressions, it is notable that in many cases, there is more variability in the year of the split than in the slope of the post-split retreat (the best examples of this are Southern Andes, Low Latitudes, and New Zealand). This suggests that differences in total post-industrial retreat are more influenced by differences in when the retreat starts than by differences in the severity of the retreat.

Variable start dates for the observed length change timeseries, with a number of regions lacking any pre-industrial representation, make comparisons with model results difficult for the pre-industrial period. Trends can be seen in the pre-industrial model output for a number of regions, but they are smaller in magnitude, and less coherent, both between climate models and between regions, consistent with the lack of global-scale temperature trends prior to post-industrial warming (Neukom et al., 2019). This is explained largely by the comparison of the default model output and the fixed climate runs (see below); in particular, for the runs using constant temperature (Fig. 5), the divergence between the constant temperature and the full climate run typically occurs in the post-industrial period. As the most coherent changes both in climate model variables and in model results occur in the last ∼150 years, we do not examine the patterns of pre-industrial length change on a per-region basis.

To understand the impact of temperature and precipitation individually in driving trends in the modelled output, we plot the primary output alongside the output with constant precipitation/constant temperature. Figures 4 and 5 show these results for each region for one climate model - IPSL - along with the smoothed annual precipitation/temperature (given in degree-days), with the same figures for the other 5 climate models appearing in supplementary material (Fig. S1-S10). Figure 6 also shows the variance in the constant precipitation/constant temperature runs relative to the variance in the primary runs. Together these 3 figures show that for most models and for most regions, temperature influences length fluctuations more than precipitation,

https://doi.org/10.5194/tc-2019-275
Preprint. Discussion started: 16 December 2019

but the relative importacet of the two factors is far from homogenous. In addition to particular models which show anomalous relative importance of temperature and precipitation in a region - for example, CCSM4 in Iceland - there are also regions where the influences of temperature and precipitation are much more equal across most models, most notably South Asia West and South Asia East. The information in Fig. 6 is also shown in Tables S1-4 (supplementary material) in order to split the level of variance explained by each climate variable into categories and provide a quantitative perspective. This data shows that there are only 4 regions where half of the models or more show precipitation either fully explains or overexplains the full-climate-driven variation: Svalbard, the Russian Arctic, South Asia West, and South Asia East. There is also only one region in which temperature fully explains or overexplains the full-climate-driven variation in fewer than half of the models: Central Asia. Overall, precipitation only explains a minimal amount of full-climate-driven variation, with a small number of outliers, while the proportion of variance explained by temperature differs more between models and regions. In Tables S3 and S4, each climate model shows a similar overall distribution across relative variance categories for both precipitation or temperature, so the OGGM response to climate signals is similar across all 6 models. This suggests that real long-term climate trends in the modelling period play a much larger role in determining glacier length changes than differences between climate models.

A notable feature of Fig. 6 is the prevalence of relative variance values greater than 1. If the values of temperature and precipitation were statistically independent in the climate model data, and OGGM's responses to temperature and precipitation were independent, we might not expect relative variance values greater than 1, as OGGM's output for the full climate runs is a response to both temperature and precipitation changes combined. However, there are several possible reasons for the observed high relative variance values, and different region/climate model combinations indicate different such reasons. In some cases - such as Central Asia in Fig. 5 - where glaciers take a long time to reach equilibrium even after the spin-up, differing rates of approach to equilibrium in the full and constant precipitation/temperature runs can cause large differences in variance; this is purely a modelling issue. In others - such as South Asia East and New Zealand in Fig. 4 - the constant precipitation run shows greater overall retreat than the full run, which is the primary cause of greater relative variance. In the South Asia East case, it seems the precipitation in the 1400-1450 climatology used for the constant precipitation run is lower than the average value for the full model run, gradually increasing the gap between the full and constant precipitation runs; in the New Zealand case, there is an increase in precipitation in the last 200 years which offsets some temperature-based retreat, which does not have an impact in the constant precipitation case. For each region/model combination, the reasons for the relative variance can be different, and it can be difficult to conclusively describe one factor or collection of factors that explains this difference.

4 Conclusions

Overall, modelling is completed successfully for an overwhelming majority of glaciers across, and we produce length change timeseries for all RGI regions for which we identify any glaciers in the Leclercq length changes inventory (all RGI regions with the exceptions of Arctic Canada North, Arctic Canada South, and Antarctica). In many regions where the Leclercq data show retreat over the 20th century, this observed retreat is within the range of modelled retreats, often with the observed retreat being amongst the steeper and earlier-starting retreats in the modelled set. This suggests that OGGM is at least qualitatively

https://doi.org/10.5194/tc-2019-275
Preprint. Discussion started: 16 December 2019

capturing major trends in glacier length in many regions, and that the modelled responses to climate trends may be slightly reduced compared to reality.

While there are regions which lack enough results to draw significant conclusions (e.g. Russian Arctic, with only one glacier modelled), and other regions where the results appear too noisy to draw significant conclusions (e.g. South Asia West), in many regions we do find clear differences between climate model runs that are larger than the variability within OGGM for each run (e.g. Caucasus/Middle East, Low Latitudes, Southern Andes). This suggests meaningful differences between the climate models used in terms of their impact on glacier evolution, and also supports the idea that OGGM results can be used to assess modelled or reconstructed climates.

Model runs driven by temperature and precipitation individually show that OGGM's response to climate forcing is a matter of some complexity, despite the ostensibly straightforward mechanics involved in the way the model calculates glacier ablation and accumulation. In almost all cases, temperature is the dominant forcing, explaining much more of the variability in glacier length than precipitation, but the sum of variability explained by temperature and precipitation individually rarely matches the total variability, and the common phenomenon of the temperature-only forcing showing greater variability than the full climate runs suggests negative feedbacks between temperature and precipitation effects on overall glacier geometry change. This demonstrates the importance of using dedicated glacier models in predicting past glacier changes, as simple temperature and precipitation proxies cannot properly capture this behaviour. This fact, combined with some regions showing considerable changes in pre-industrial glacier lengths, illustrates the need for appropriately sophisticated glacier models to understand changes on multi-centennial to millennial timescales even for periods with less overall temperature change. Recent, more rapid glacier changes which are better observed and more frequently the focus of modelling efforts require these multi-centennial to millennial timescale historical runs for proper context. The next step, given that most glaciers in this study were modelled successfully, is to attempt to model entire global glacier inventories over similar timescales, in order to fully understand the total changes in each region, including volume change as a contributor to sea level change.

Code availability. Code to run OGGM (Maussion et al., 2019) is available at http://oggm.org along with supporting documentation

Author contributions. Study concept devised by HG. Model runs and analysis performed by DP. Manuscript written by DP with contributions by HG.

Competing interests. The authors declare that they have no conflicting interests.

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References

CGIAR-CSI: SRTM 90m Digital Elevation Data, http://srtm.csi.cgiar.org/, 2019.

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D., and Unnikrishnan, A. S.: Sea Level Change, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 1137–1216, Cambridge University Press, 2013.

Cogley, J. G.: Geodetic and direct mass-balance measurements: comparison and joint analysis, Ann. Glaciol., 50, 96–100, https://doi.org/10.3189/172756409787769744, 2009.

Daigle, D. and Kaufman, D.: Holocene climate inferred from glacier extent, lake sediment and tree rings at Goat Lake, Kenai Mountains, Alaska, USA, J. Quarternary Sci., 24, 33–45, https://doi.org/10.1002/jqs.1166, 2009.

de Ferranti, J.: Viewfinder Panoramas DEM3, http://viewfinderpanoramas.org/dem3.html, 2019.

Goosse, H., Barriat, P.-Y., Dalaiden, Q., Klein, F., Marzeion, B., Maussion, F., Pelucchi, P., and Vlug, A.: Testing the consistency between changes in simulated climate and Alpine glacier length over the past millennium, Climate of the Past, 14, 1119–1133, https://doi.org/10.5194/cp-14-1119-2018, 2018.

Jones, P. and Harris, I.: CRU TS3.21: Climatic Research Unit (CRU) Time-Series (TS) Version 3.21 of High Resolution Gridded Data of Month-by-month Variation in Climate (Jan. 1901- Dec. 2012), https://doi.org/0.5285/D0E1585D-3417-485F-87AE-4FCECF10A992, http://catalogue.ceda.ac.uk/uuid/ac4ecbd554d0dd52a9b575d9666dc42d, 2013.

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

Marzeion, B., Jarosch, A. H., and Hofer, M.: Past and future sea-level change from the surface mass balance of glaciers, The Cryosphere, 6, 1295–1322, https://doi.org/10.5194/tc-6-1295-2012, 2012.

Maussion, F., Butenko, A., Champollion, N., Dusch, M., Eis, J., Fourteau, K., Gregor, P., Jarosch, A., Landmann, J., Oesterle, F., Recinos, B., Rothenpieler, T., Vlug, A., Wild, C., and Marzeion, B.: The Open Global Glacier Model (OGGM) v1.1, Geosci. Model Dev., 12, 909–931, https://doi.org/10.5194/gmd-12-909-2019, 2019.

Neukom, R., Steiger, N., Gomez-Navarro, J., Wang, J., and Werner, J.: No evidence for globally coherent warm and cold periods over the preindustrial Common Era, Nature, 571, 550–554, https://doi.org/10.1038/s41586-019-1401-2, 2019.

NSIDC: Greenland Ice sheet Mapping Project (GIMP) Digital Elevation Model, https://nsidc.org/data/measures/gimp, 2019.

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

Oerlemans, J.: Holocene glacier fluctuations: is the current rate of retreat exceptional?, Ann. Glaciol., 31, 39–44, https://doi.org/10.3189/172756400781820246, 2017.

OGGM e.V.: Open Global Glacier Model, https://oggm.org/, 2019.

PAGES 2k Consortium: Continental-scale temperature variability during the last two millennia, Nature Geosci., 6, 339–346, https://doi.org/10.1038/ngeo1797, 2013.

PAGES 2k Consortium: A global multiproxy database for temperature reconstructions of the Common Era, Scientific Data, 4, https://doi.org/10.5194/cp-11-1673-2015, 2017.

PAGES 2k-PMIP3 group: Continental-scale temperature variability in PMIP3 simulations and PAGES 2k regional temperature reconstructions over the past millennium, Climate of the Past, 11, 1673–1699, https://doi.org/10.5194/cp-11-1673-2015, 2015.

https://doi.org/10.5194/tc-2019-275
Preprint. Discussion started: 16 December 2019

Parkes, D. and Marzeion, B.: Twentieth-century contribution to sea-level rise from uncharted glaciers, Nature, 563, 551–554, https://doi.org/10.1038/s41586-018-0687-9, 2018.

Recinos, B., Maussion, F., Rothenpieler, T., and Marzeion, B.: Impact of frontal ablation on the ice thickness estimation of marine-terminating glaciers in Alaska (in review), The Cryosphere Discussions, https://doi.org/10.5194/tc-2018-254, 2018.

RGI Consortium: Randolph Glacier Inventory (RGI) - A Dataset of Global Glacier Outlines: Version 6.0., https://doi.org/10.7265/N5-RGI-60, https://www.glims.org/RGI/, 2017.

Schmidt, G., Jungclaus, J., Ammann, C., Bard, E., Braconnot, P., Crowley, T., Delaygue, G., Joos, F., Krivova, N., Muscheler, R., Otto-Bliesner, B., Pongratz, J., Shindell, D., Solanki, S., Steinhilber, F., and Vieira, L.: Climate forcing reconstructions for use in PMIP simulations of the Last Millennium (v1.1), Geosci. Model Dev., 5, 185–191, 2011.

Taylor, K., Stouffer, R., and Meehl, G.: An Overview of CMIP5 and the Experiment Design, Bull. Amer. Meteor. Soc., 93, 485–498, https://doi.org/10.1175/BAMS-D-11-00094.1, 2012.

WGMS (World Glacier Monitoring Service) and NSIDC (National Snow and Ice Data Center): World Glacier Inventory, http://nsidc.org/data/glacier_inventory/index.html, 1989.

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A. P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L. N., Cáceres, B. E., Casassa, G., Cobos, G., Dávila, L. R., Granados, H. D., Demuth, M. N., Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J. O., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V. V., Portocarrero, C. A., Prinz, R., Sangewar, C. V., Severskiy, I., Sigurdsson, O., Soruco, A., Usubaliev, R., and Vincent, C.: Historically unprecedented global glacier decline in the early 21st century, J. Glaciol., 61, 745–762, 2015.

https://doi.org/10.5194/tc-2019-275
Preprint. Discussion started: 16 December 2019

The Cryosphere
Discussions

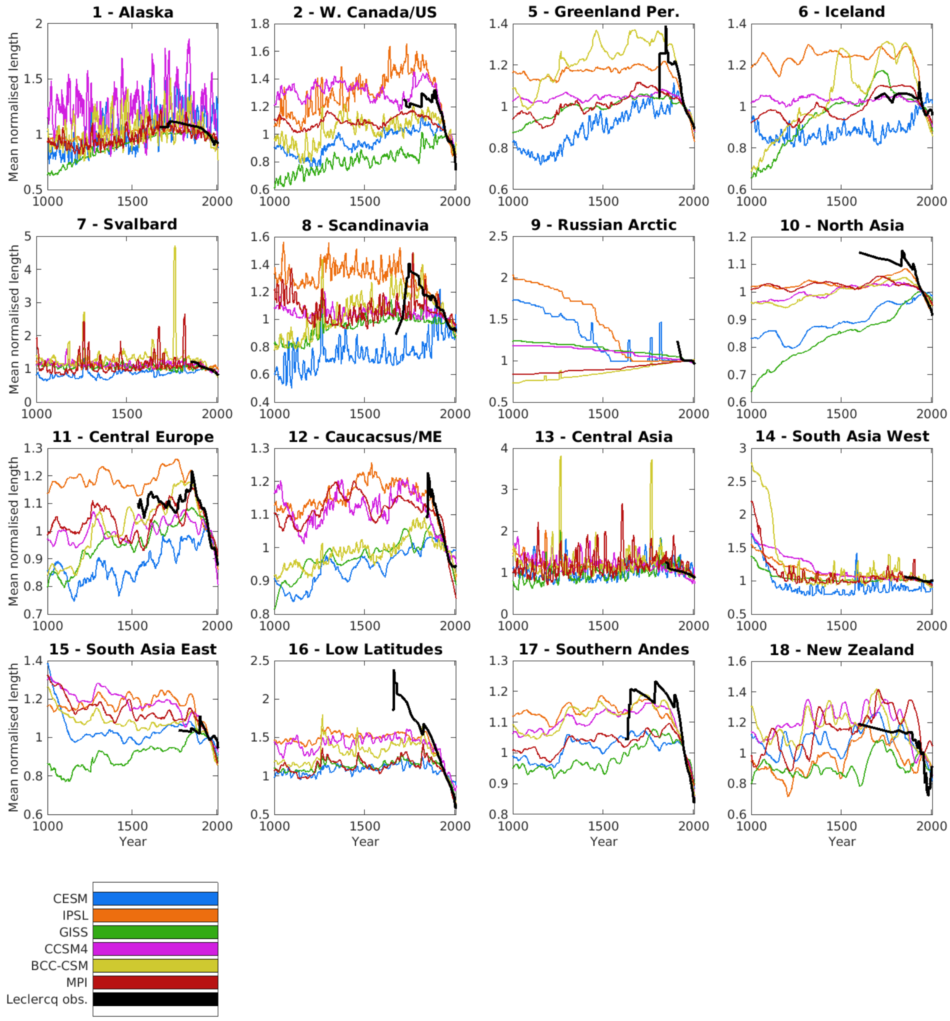

Figure 1. Length changes from 1000-2004 CE across 16 RGI regions, modelled by OGGM using 6 separate GCM products (CESM, IPSL, GISS, BCC-CSM, CCSM4, and MPI), and compared to length change observations from the Leclercq (2014) dataset. Each glacier in both the OGGM runs and Leclercq observations has its length changes normalised relative to the 1950 length in the run output or observations respectively. The number of glaciers that contribute towards the mean in each region are listed in Table 1.

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Preprint. Discussion started: 16 December 2019

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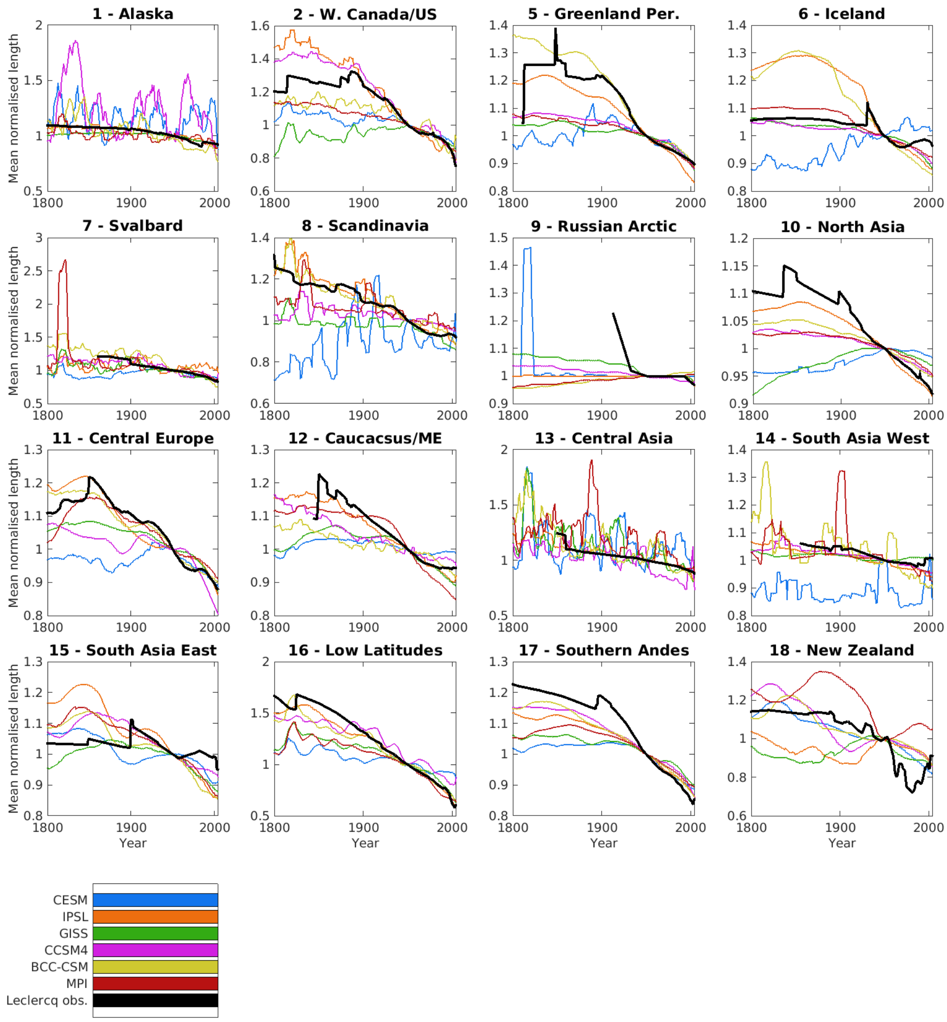

Figure 2. Length changes from 1800-2004 CE across 16 RGI regions, modelled by OGGM using 6 separate GCM products (CESM, IPSL, GISS, BCC-CSM, CCSM4, and MPI), and compared to length change observations from the Leclercq (2014) dataset. The data and processing used to create this graph is identical to that used in Fig. 1, but restricted to 1800 onward.

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Preprint. Discussion started: 16 December 2019

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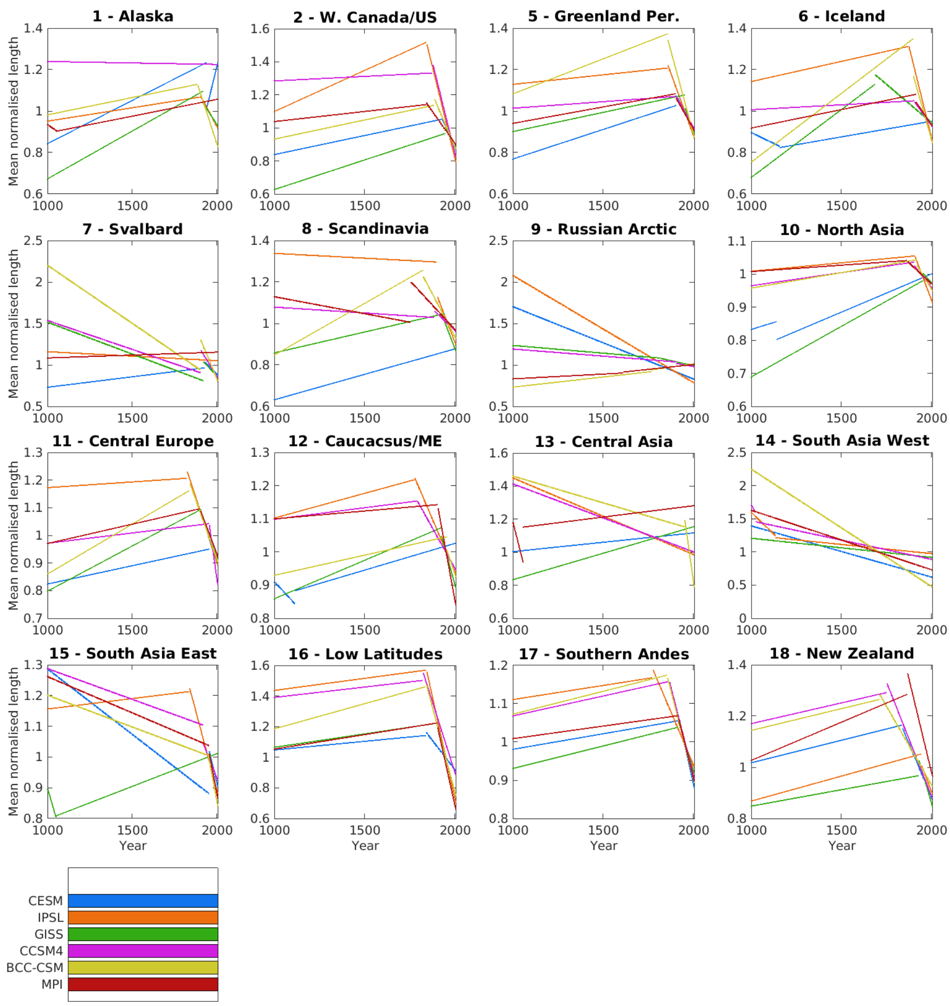

Figure 3. Regional length changes represented by an optimised 2-part split regression. For each modelled timeseries of mean normalised glacier length, a split is produced for each year between 901 and 1954 and a simple linear regression performed separately for years up to and including the split year, and years after the split year. The year which maximises the sum of the r^2 values for these two regressions is considered optimal, and both regression lines are shown for the optimal year, for each region and climate model.

https://doi.org/10.5194/tc-2019-275
Preprint. Discussion started: 16 December 2019

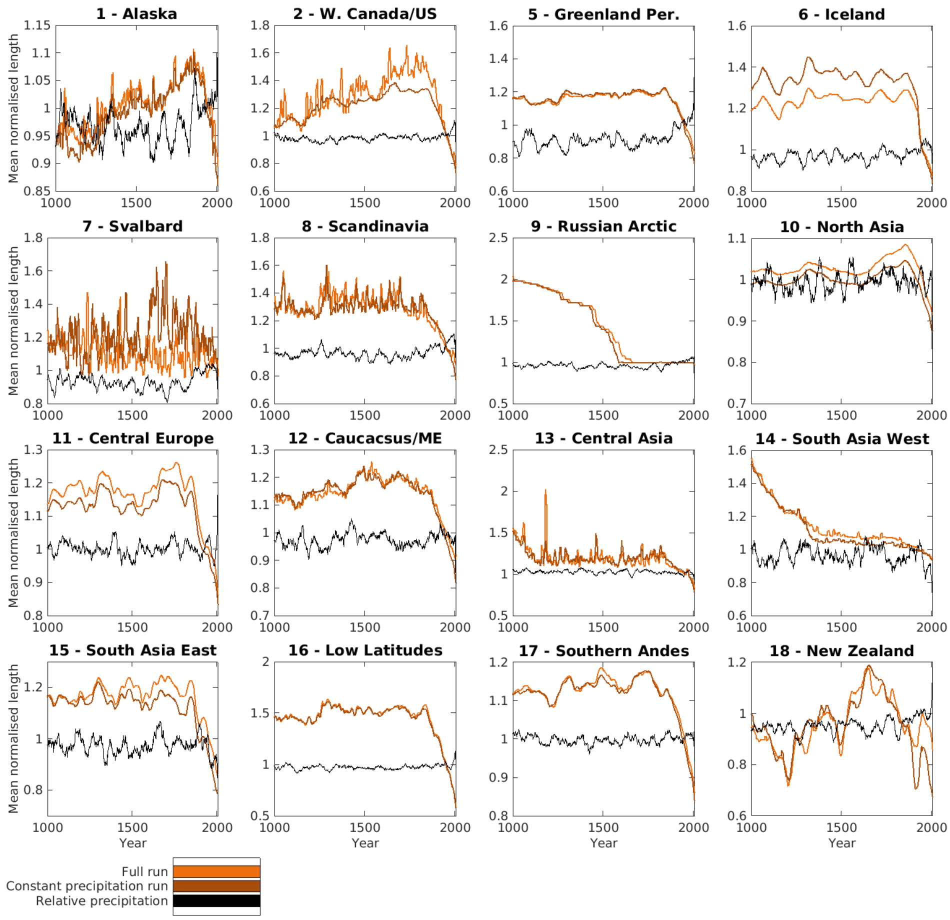

Figure 4. Regional length changes for 1 model (IPSL) comparing fully climate run and constant precipitation run, shown with relative precipitation (annual precipitation normalised to 1900-1950 mean climate). The constant precipitation run lengths are normalised to the full climate run 1950 length, to better illustrate differences.

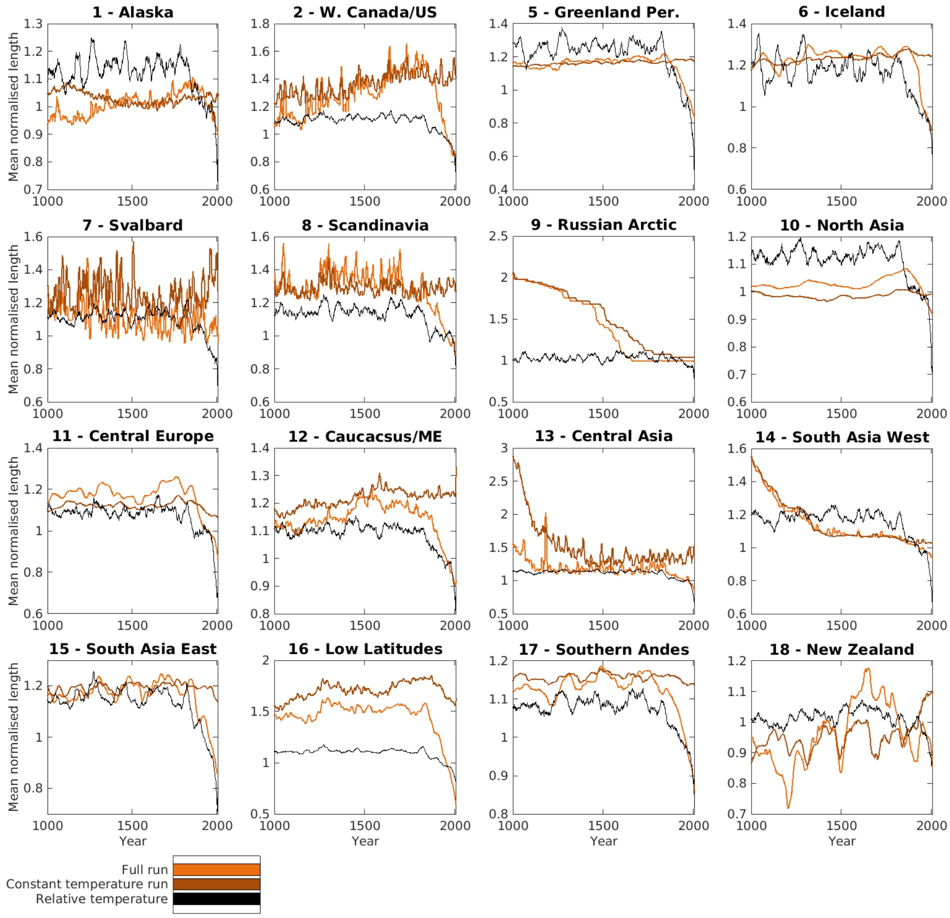

Figure 5. Regional length changes for 1 model (IPSL) comparing fully climate run and constant temperature run, shown with relative melt-relevant temperature (annual degree-day sum normalised to 1900-1950 mean climate). Relative temperature is inverted, so that the direction of any trend corresponds to the expected impact on glacier length. The constant temperature run lengths are normalised to the full climate run 1950 length, to better illustrate differences.

https://doi.org/10.5194/tc-2019-275
Preprint. Discussion started: 16 December 2019

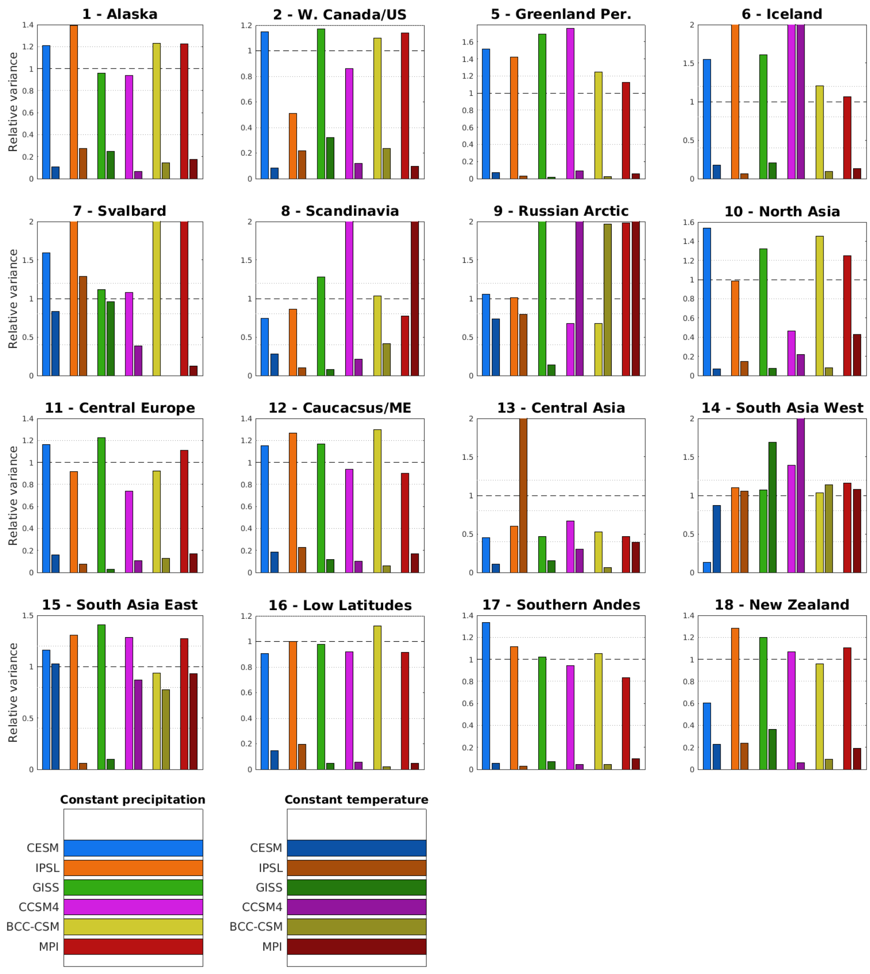

Figure 6. Relative variance of the constant precipitation and constant temperature runs to the full climate model run for each of the 6 climate models used. A relative variance of 1 (dashed line) indicates the same overall variance in the constant prec/temp run as in the full climate run. A low relative variance in the constant precipitation run indicates a small impact of temperature on glacier length changes, and vice versa. A high relative variance in the constant precipitation run may indicate a large impact of temperature on glacier length changes (and vice versa), though in cases of relative variance greater that 1, there are several possible explanations for this behaviour. The same information is shown numerically in supplementary Tables S1-4, sorted into categories - the borders of these categories are shown here by the dotted lines.

https://doi.org/10.5194/tc-2019-275
Preprint. Discussion started: 16 December 2019

The Cryosphere Discussions
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Table 1. Breakdown of the glaciers modelled by region, showing the two reasons glaciers may be removed from contributing to regional means: the glaciers being flagged in the RGI as marine- or lake-terminating, and a failure in the modelling process.

Region	Total glaciers	Marine/lake-terminating	Model failures						
			All models	CESM	IPSL	GISS	BCC-CSM	CCSM4	MPI
Alaska	20	8	0	0	1	1	1	2	0
W. Can/US	34	0	0	2	4	0	4	0	5
Greenland Per.	74	37	0	0	9	5	3	6	3
Iceland	6	0	0	0	2	1	2	2	1
Svalbard	15	3	0	0	1	1	0	2	1
Scandinavia	14	0	1	0	0	0	0	0	0
Rus. Arctic	13	12	0	0	0	0	0	0	0
North Asia	8	0	0	0	0	0	0	0	0
Cen. Europe	89	0	0	0	7	3	28	3	1
Cauc./M.East	31	0	0	0	2	2	1	1	3
Cen. Asia	27	0	0	0	1	0	1	0	0
S Asia West	5	0	0	0	0	0	0	0	0
S Asia East	6	0	0	0	0	0	0	0	0
Low Latitudes	17	0	0	0	7	0	0	0	3
S Andes	50	13	1	0	0	0	0	1	0
New Zealand	3	0	0	0	0	0	0	0	0
Global	412	73	2	2	34	13	40	17	17