We thank the reviewers for the constructive reviews and suggestions. The comments by the reviewers are in indented blocks and italic fonts. Our response follows each comment and changes in the manuscript are in quotation marks.

Response to Reviewer 1

Major comments

> *As mentioned by the authors, scaling sea level rise at the scale of Greenland using results from only a few glaciers is highly speculative. However, this is still what is done in this paper without assessing the uncertainty of such a scaling. It would be important to quantify the uncertainty in the scaling by comparing results obtained with a subset of models. Also, do you think that 12 glaciers are representative of Greenland? They are many kind of different glaciers, with or without marine terminating fronts, with or without ice shelves, with completely different geometries and fjord conditions; some glaciers are mostly impacted by changes in ice front position, or subglacial hydrology(with different types of subglacial hydrology regimes, ...)? So is it reasonable to use such a small sampling of glaciers and consider that their behavior is representative of the 200 glaciers of the Greenland ice sheet?*

We agree with the reviewer that the accurate estimate of the contribution of Greenland outlet glaciers to future sea level rise will only be possible when all 200+ glaciers will be accurately modeled. The Fig.14 in our paper, first of all presents the test of the "scaling up technique" used by Nick et al. (2013) who estimated the total contribution of outlet Greenland glaciers by using results of simulations made only for four major Greenland glaciers. Note that Nick et al. (2013) did not tested whether a correlation between present-day discharge and future sea level rise even exists. Here we used 12 glaciers which differ significantly by discharge and location. We do not claim that they properly represent all Greenland glaciers but, still, this is an obvious step forward compare to the previous study. We found (Fig. 14) that some correlation between present-day discharge and the future contribution to sea level rise does exist . Since we consider only a small subset of Greenland glaciers and only some sources of uncertainties, we do not think that the detailed uncertainties analysis of the relationship between discharge and sea level rise would be very helpful. However, we demonstrated how the uncertainty ranges by the choice of glaciers in the supplementary part Figure S7. Determining SLR from these 4 different glaciers leads a SLR range of (10.3-16.8 cm), which we ist no mentioned in our discussion.

> *I don't understand why the water conditions at 400 m depth are used in the plume model for all the glaciers. All the fjords and glaciers have very different geometry conditions (with sills, ...) that should be taken into account in order to have the right conditions for the plume model. It looks like the authors are trying to set-up the initial conditions so that the glaciers are in steady state.*

This is a misunderstanding and we no improved this part of the manuscript (Section 3.4) to make more clear how we constructed the T-S profile and why we use "the water conditions at 400 m depth". Firstly, it is important to note that for all 12 glaciers used in this study, there are at least some CTD profiles from the adjacent fjords and, in spite of some problems with CTD profiles (discussed in the manuscript), the CTD profiles are always our first choice to force the plume model. However, CTD profiles are not yet available for all 200+ Greenland glaciers. This is is why (in addition to CTD profile) we tested whether T-S profiles in Greenland fjords can be constructed using the results of the ocean reanalysis project. Since the reanalysis data are only available for the open ocean, we used the nearest to the fjord's mouth reanalysis grid cells with the depth 200, 400 and 700 m (these are the top three vertical levels in the reanalysis data set). By comparing reanalysis data with the corresponding CTD data (Fig. 4 and 5) we found that at depth 200 and 400 m reanalysis and CTD data are in reasonable agreement while for the 700 m depth they are completely off, which is explained by the fact the 700m depth-points are always located outside the continental shelf .Therefore they are not appropriate to produce vertical temperature profile in the fjords . Therefore instead of interpolated between 400 and 700 m values, we choose to prescribed below 400 m as constant temperature equal to temperature at the depth 400 m in the reanalysis data. We then compare submarine melt computed using CTD profiles with those have been computed using temperature and salinity profiles from 200 and 400 m depths in the reanalysis data. We found that results are in reasonable agreement. Therefore we recommend as a temporal option (before better data will be available) to use the nearest gridcells with depth 200 and 400 m to construct T and S profile from the reanalysis data for the fjords for which CTD data are not yet available. Moreover, we now show -in the new version of the manuscript- that if we construct temperature files from reanalysis data and consider sill (Fig. S2, supplementary information), the discrepancy grows bigger between CTD measurement close to the glacier front and to the reconstructed TS profile (Fig, S3 supplementary Information) four our selected glaciers.

Many glaciers experienced large changes over the past couple of decades and they are therefore not in steady-state. I think it is more important to have initial conditions close present state than close to a steady-state, especially as initial conditions impact the system for a very long time (much longer than the simulation time in this paper). Furthermore, it is difficult to add the present trend to the simulated changes as glaciers are not exactly linear systems.

The meaning of the "present day" should be properly defined – otherwise it causes confusion. We did not assume that the glacier are in the equilibrium state at present, i.e. in the year 2018. In our paper under "present day" we mean the years 2000 which we use as the starting time for all our forced simulations. The choice of the year 2000 is motivated by the fact that the mass loss of GrIS during the last decade of 20the century was rather small (ca. 0.1 mm/yr) compare to that has been observed in the 21st century. This justify our assumption about quasiequilibrium state of Greenland glaciers at the beginning of experiments. Some inconsistency arises from the fact that the database (BedmACHInev2) we used to initialized the glaciers at the year 2000 are actually based on the measurements made in 2008/2009. However even the total contribution of GrIS to global seal level rise during the first 8 years of the 21st century was only about 3 mm and glaciers contributed not more than half of that. This is of course a very small number compared too our total estimate of 50 mm of glaciers contribution during the entire 21st century. For this reason we see no need in adding "present day" trend to the results we obtained. To the contrary, we extracted from the results a very small trend diagnosed in the control (unforced) run. We now state in section 4.1. (page 12): "We chose the year 2000 as the quasi-equilibrium initial state for "future" climate change simulations since the mass loss of GrIS during the last decade of 20the century was rather small (ca. 0.1 mm/yr in sea level equivalent) compare to that has been observed in the 21st century ((Vaughan et al., 2013)."

I don't understand why only one atmosphere model is used for the future forcing while several ocean models are used.

It is well-known that for the entire GrIS contribution to sea level rise, climate change scenarios (both in term of GHGs concentration and the model output) are the major source of uncertainties. In this this study we decided to concentrate on the new issue, namely glacier-ocean interaction. Therefore, we used output of only one regional climate model for a single climate change scenario (RCP8.5) and concentrated on the uncertainties related to parameterizations of submarine melting and calving. We agree with the reviewer that applying another atmospheric model would introduce additional uncertainties in sea level rise via different smb and subglacial discharge. We would like to address this in future work.

There is also no clear distinction between the spread in results caused by the different climate scenarios and the different initial states, and their relative importance for the different glaciers. Is it more important to improve the external forcings (and which one) or to improve the initial conditions to reduce the uncertainty in future glacier's evolution?

We do not agree with the reviewer here. In Figure 15 we demonstrate the spread of results for each single forcing scenario and therefore attribute the spread to the different initial states, thus beta, and fwd. For clarity we state now in the section future results: “We attribute the major source of uncertainty to the different combinations of the model parameters fwd and beta. “

It seems like the authors read a coupled of references [Nick et al., 2013; Goelzer et al., 2013], and keep using them all over the manuscript. They are also many regional models (that are not 1D) that should be used to compare the results of this study.

Citing of Nick and Goelzer is natural since we used a similar approach and compare our results with these two studies. Of course, we are aware about regional Greenland ice sheet modeling and, although in most cases it is difficult to compare directly our results with regional modeling, , we included a comparison to other regional models for a broader discussion in the introduction aswell as in the discussion part.

Finally, I must say that I am a bit tired of seeing studies based on flowline models in 2018. I agree that such studies are still very useful to investigate new processes for example, but they should not be used to do future projections of ice sheets, given the importance of buttressing, lateral effects, complex topography ... when 2D regional models can be run at high resolution and provide more accurate results.

We respect the reviewer's opinion on the issue which models should be used for future projections of ice sheets. However, the focus of our study is not on future projection of the Greenland Ice Sheet but rather on the response of outlet marine-terminated glaciers to climate change and, primarily, on the analysis of uncertainties related to two poorly constrained processes: submarine melt and calving. We appreciate the importance of buttressing, lateral effects and complex topography which unavoidably are treated in a rather simplistic way in the 1-D model. However, we doubt whether at present 2D models can really provide “more accurate results” since accurate modeling of marine terminated glaciers would require as input accurate knowledge of present and future (i) fjord bathymetry, (ii) temporal variability of the 3D fields of temperature, salinity and velocity in the fjord, and (iii) the spatial-temporal distribution of subglacial discharge of melt water into the fjords. Even at present all these characteristics are not accurately known for Greenland glacier and in most cases they are not known at all. At the same time we agree that the paper now benefits from the discussion of model limitations and future perspectives.

Line by line comments

p.1 l.6: crudely → simplistic (models use simple parameterizations because the processes remain unknown as mentioned at the beginning of the sentence)

Agreed, we replaced “crudely” with “simplistically”

p.1 l.10: Is the regional climate model used only for the SMB or also for other properties?

The other property is surface runoff as mentioned in the sentence.” ...forcing the model with changes in surface mass balance and surface runoff…,”

p.1 l.12 (and l.14 and l.15): use present tense instead of past in the abstract: used → used.

Agreed, we adapted the tense.

p.1 l.22: the scaling is quite speculative. What happens if you do the scaling with a smaller set of glaciers? What is the uncertainty in this scaling?

We thank the reviewer for this interesting suggestion. As mentioned above, we derived now such an uncertainty as proposed by taking 4 (same number as Nick et al) different glaciers and determine a minimum and maximum SLR number (Fig. S7). The range derived from this method I mentioned now in the discussion part of the manuscript.

p.1 l.19 and l.23: If I understand correctly, the numbers given here do not include the current trend in mass loss from the Greenland ice sheet (13.8 cm in the conclusions). This is rather confusing and provides numbers smaller than expected.

The numbers given in the abstract (14 mm for twelve glaciers and 50 mm obtained by scaling up for all glaciers) can be considered as complimentary to the numbers order of 100 mm computed in the coarse-resolution GrIS models (e.g. Calov et al., 2018) because in the latter the mass loss of the GrIS is mostly controlled by changes of SMB, while mass loss of outlet glaciers is primarily controlled by increased submarine melt. We now write: "… we estimate the mid-range contribution of all Greenland glaciers to 21st-century sea level rise to be approximately 50mm. This number adds to SLR derived from a stand-alone, coarse resolution ice sheet model and thus increases SLR by over 50 \%."

p.2 l.4: "Two processes are largely responsible": What are the other processes that account for mass loss to a lesser extent?

We added the percentage in brackets: (60 %) surface melting and (40 %) dynamical processes.

p.2 l.6: "marine-terminating" → "marine terminating"

Agreed.

p.2 l.8: It is not just warming of the ocean, but also changed in the circulation.

We agree, the circulation changes led to the warming of the ocean. The sentence now reads: "...which can in turn be attributed to a warming of the subpolar North Atlantic ocean, induced by circulation changes, and increased subglacial discharge"

p.2 l.9: I doubt that the lower contribution in Fettweis et al. [2013] is 0 cm, it should be 50 mm (9 ± 4 cm). This seems rather contradictory with the actual contribution.

We thank the reviewer for spotting this mistake. 0 cm was cited in Fettweis et al. 2013 from other studies. We changed the number to 50 mm.

p.2 l.13: Adding references to papers that detail the limitations of modeling of the Greenland ice sheet would be appropriate (e.g. Goelzer et al. [2017]; Khan et al. [2014]).

We thank the reviewer for this suggestion. We cited now: "The contribution of the second process remains highly uncertain because processes related to the response of marine terminated Greenland glaciers are still not properly represented in the contemporary GrIS models (Straneo and Heimbach, 2013; Khan et al., 2014; Goelzer et al., 2017)."the above-mentioned literature.

p.2 l.18-20: I think this is disregarding all the efforts made to improve continental scale models, as some models now have a resolution of about 1 km in marine terminating glaciers [Goelzer et al., 2018]. This is also a bit oversimplifying the problem: the limitations of numerical models are not just resolution, there is also limited observations,external forcings not appropriate, ... So this part of the introduction has to be more balanced.

Yes, as cited above we now write:"The contribution of the second process remains highly uncertain because processes related to the response of marine terminated Greenland glaciers are still not properly represented in the contemporary GrIS models (Straneo and Heimbach, 2013; Khan et al., 2014; Goelzer et al., 2017).

p.2 l.21-25: Following along the same line, I think jumping from continental scale 3D models to 1D flowline models is a bit reductive, as they are many things in between. Several regional models with 2D or 3D models are starting to show interesting results [Muresan et al., 2016; Bondzio et al., 2017]. Some studies even included representation of ocean with a plume model [Vallot et al., 2018]. So I think the introduction should be improved and not just reduced to Goelzer et al. [2013] and Nick et al. [2013].

We thank the reviewer for pointing out this different studies. We mention now these and several other applications of 3D models to study response on regional and shorter time scales. As far as a very interesting paper by Vallot et al. (2018) nicely illustrates that high-resolution and physically based modeling of glacier-ocean interaction is already possible but absolutely impractical for the study of glacier response to global warming. While Vallot et al. (2018) studied only one melt season with the glacier model., they were able to run plume model only for 10 minutes and only for a small fraction of the ice front. Therefore we cannot see an alternative to highly simplified parameterization of the glacier-ocean interaction when the centennial time scale response is concerned. However, we now mention the other studies in the introduction (p.2-3):"For regional settings, 3D models with a simple ocean melting parameterization were applied to study the historical (last 20 -30 years) retreat of Jakobshaven Isbrae (Muresan and Khan,2016; Bondzio et al., 2017). A more advanced treatment of submarine melt rate was done by Vallot et al.(2018). They coupled a plume model based on the Navier-Stokes equations with a full-Stokes ice sheet model. With this off-line coupling, glacier dynamics for one melt season were simulated for Kronebreen Glacier in Svalbard.
"

p.2 l.32: "that that"

Deleted.

p.3 l.1: You just mentioned that the approach from Nick et al. [2013] is not appropriate, but you follow the same one, just with slightly more glaciers. I am not sure I understand the logic here.

We did not state that the approach from Nick et al "is not appropriate". This study has obvious limitations, such as using of only four largest glaciers to project the the entire 200+ glaciers contribution to sea level rise as well as a very simplistic parameterization for the submarine melt. We wrote that "we followed an approach similar to Nick et al. (2013) but with several notable improvements" and our major improvement is using of more glaciers and more physically based parameterization for submarine melt.

p.3 l.28: "with 3D ice sheet model" → "with 3D ice sheet models"

Agreed, changed in the revised version.

p.3 l.30: "we used instead" → "we use instead"

Agreed, changed in the revised version.

p.3 l.31: I agree that continental scale Greenland models are not the best tool to study these processes, but why not use 2D basin models that would at least include lateral deformations and buttressing is important to correctly capture the behavior of narrow outlet glaciers terminating in fjords.

We thank the reviewer for his suggestion but we want to point out that 1D flowline models include lateral deformation and buttressing in a simplistic manner. We , however mention the limitation of the 1D model in the discussion: "Additionally, the 1D flowline model treat lateral processes in a simplified manner, so that more complex bedrock geometries (e.g. branching of glaciers, individual sills, unsymmetrical valley forms) are poorly represented in these estimations."

p.4 Eq.2: Can you explain the choice made to incorporate the lateral stress?

The lateral stress term is necessary because the glaciers we considered for this study, like most Greenland marine-terminating glaciers, narrow-down toward their terminus (width of the order of 5 km, besides Petermann), with velocity of the order of 1000 meters per year (10 000 m/a for Jakobshavn Isbrae, according to present observations), making it impossible to neglect lateral drag. The stress term was derived e.g. by Veen and Whillans (1996), and used by various authors since (e.g. Nick et al., 2013; Enderlin et al., 2013; Schoof et al, 2017).We now write in the manuscript: "The lateral stress term likewise used by e.g. Nick

et al. (2013); Enderlin and Howat (2013); Schoof et al. (2017), and originally derived by Van Der Veen and Whillans (1996),
is necessary to account for lateral resistance in fast-flowing, laterally-confined glaciers typical for Greenland."

p.4 l.9: Where does the basal sliding coefficient come from?

The basal sliding coefficient (equation 2) was determined, along with other uncertain parameters, from calibration to present-day state. We now give a list ob basal sliding coefficient and other dynamical parameters in the supporting information (table S2).

p.4 Eq.5: How different is this from simply applying water pressure at the front?

It is not and we thank the reviewer for spotting the lack of explanation here. We now introduce the description of equation 5 with "while at the calving front x cf balancing the longitudinal stress with the hydrostatic sea water pressure and incorporating the flow law of ice yields longitudinal stretching".

p.4 l.21: So is there a point exactly at the grounding line position? This should be better explained. Also, how is treated the stretching of the grid, in particular the variables assigned to the new grid points?

Yes, there is. We now write: "Grid stretching is performed so that there is always a cell edge at the interpolated grounding line position. The new calving front position is determined so that the total glacier volume is not modified by interpolation. For every new point in the interior, model variables are interpolated from previous grid. The first grid point at the ice divide remains unchanged. If ice grid points on the new grid lie outside the ice domain on the previous grid, as it is typically the case for the last cell before the calving front, ice thickness from the last grid cell is extended.

p.4 l.27: How about the ice front? Does it evolve with time? And following what criteria? You need to describe the subgrid-scale treatment of the ice front.

We agree with the reviewer and now describe the subgrid-scale and ice-front treatment in section 2.3 (Coupling between glacier and plume model) as follows:
"If there is no floating tongue, submarine melting is applied to the last grounded cell, otherwise it is applied starting from the first floating cell.

Thus the submarine melt rate reduces the thickness of the glacier cell. A reduced thickness at the first floating cell or last grounded cell leads to grounding line retreat since the grounding line position is determined by interpolation of the ice thickness above flotation at each time step. Thinning the last floating cell leads to calving front retreat by either melting the total cell or by calving, which increases with thinning. "

p.5 l.2: A quick explanation of the plume model in a few sentences should be added.

Agreed, for completeness we added and described now the equations of plume model.

p.5 l.8: How is a vertical profile of melt applied to a 1D model, in which there is basically no vertical dimension? So what values is used for the melt (maximum, average, ...)?

The cumulative melt rate is calculated as a volume flux and added to the mass balance term.
The integral (cumulative melt rate) is partitioned over various glacier
cells (or only one cell) in the case of a tidewater glacier. This total submarine melt rate, in a cell by cell basis, is substitute as the submarine melt rate $\dot{M}$ per units of length for each glacier cell. If

there is no floating tongue, submarine melting is applied to the last grounded cell, otherwise it is applied starting from the
first floating cell.
We describe now in more detail with the accompanying equations the treatment of submarine melt rate (page 7 until line 20).

p.5 l.12: What happens above the plume? Zero melt?

We thank the reviewer for spotting this lack of information.
Above the plume, so if the plume ceases, we set the melt rate to a minimum background melt which is given by the last melt value of the ceasing plume. We added the important information in the revised version of the paper: ”If the plume already ceases before reaching the calving front x cf , we numerically introduce a minimal background melting determined by the last melt rate value before the plume ceased.”

p.5 l.17: I don't understand "added to the vertical mass balance term B". Is the melt applied to retreat the ice front? Or just to thin the ice close to the ice front? This melt should cause ice front retreat.

We thank the reviewer for mentioning this unclarity. The melt is applied to thin the front, and does cause retreat if the cell is totally melted. Also thinning subsequently leads to calving, which then cause the ice front to retreat as well.
We explicitly describe the ice front treatment of the glacier model in the revised version of the paper.:”Thus the submarine melt rate reduces the thickness of the glacier cell. A reduced thickness at the first floating cell or last grounded cell leads to grounding line retreat since the grounding line position is determined by interpolation of the ice thickness above flotation at each time step. Thinning the last floating cell leads to calving front retreat by either melting the total cell or by calving, which increases with thinning.”

p.6 l.1: "Also, did we include" → "We also included"

Adapted.

p.6 l.9 "BedmACHINEev2" → "BedMarchine v2". Also there is new version [Morlighem et al., 2017] that compiled all existing bathymetry data around the Greenland. p.6

We are aware of this new data set which we used when constructed vertical temperature profiles from the reanalysis data. However we derived glacier geometries when this dataset was not yet available and we had no time to repeat this work with the new dataset. We will use it in our future work.

l.15:"in the ice sheet" → "in a previous ice sheet"
The sentence is changed to: “The former two sources are computed directly by the ice sheet model SICOPOLIS (Calov et al., 2018).”

p.6 l.24: Why not use the mask in Calov et al. (2018)? Combining difference sources for the different datasets might lead to some inconsistencies between the datasets.

We used the same ice mask as it is the model out put from Calob et al. (2018). For clarity we now write: “The entire basal water flux (runoff, basal melt, and water from the temperate layer) is routed by the hydraulic potential using a multi-flow direction flux routing algorithm, as described in (Calov et al., 2018). All water transfer is assumed to be instantaneous. Water that passes through the boundary of prescribed SICOPOLIS ice mask is assigned to the closest glacier within a maximum distance of 50 km.

p.6 l.26: Explain that the change in "basal melt" refers to ice shelf basal melt and not grounded ice basal melt. I was initially confused given that the previous paragraph talks about subglacial hydrology.

Basal melt here is the melt under the grounded ice sheet, that does as well contribute with the surface runoff to the subglacial discharge. For clarity we now write: "Subglacial discharge represents the sum of basal melt (melt under the grounded ice sheet), water drainage from the temperate layer and surface runoff".

p.7 Eq.9: To be honest I don't like this flux correction in the SMB. The problem of inconsistent datasets and initialization procedures is a real problem that we are facing as a community, and that deserved better treatment than a simple flux correction. This is calibrated for the initial state, but as the glacier evolves with time it is most likely not to be valid anymore. How does this correction impact the results?

The need for using of flux correction or similar methods originate from imperfectness of climate and ice sheet models and there is no reason to like it. Eventually, when ice sheet models will be improved, the flux correction will be abandoned as it happened already in the climate modeling community. However, at present, it is not possible to simulate accurately present-day elevation and spatial extend of GrIS using the SMB obtained from regional climate models. This is why we believe that using of flux correction is superior compared to using of a completely unrealistic initial state of GrIS simulated with the realistic SMB, especially, for the purpose of modeling GrIS response to climate change on centennial time scale. The dependence of simulate sea level contribution on the used corrected flux does exist, however, we found it to be not very strong for most of glaciers, by performing experiments with different relaxation times. Such weak dependence can be explained by the fact that for the outlet glaciers (unlike the rest of GrIS), changes in SMB plays only a secondary role in glaciers retreat compare to changes in submarine melt and calving.

p.8 l.19: I am confused about this comparison at different depths? Why not use temperature profiles over the entire depth? Also how did you choose these depths? Do they correspond to the depth of warm or cold water? Or the changes in the thermocline? What is the rational for this choice?

As we explained above (and we make it now more clear in the revised manuscript) we used the reanalysis data as the fallback option for the fjords for which there are no CTDs available. The reanalysis data are available at the regular grid and at the vertical level 5, 30, 50, 100,200, 400, 700, etc ...3000 m. Since most of submarine melting occurs below 100 m and typical depth of Greenland fjords is up to 700m, we restricted our comparison of (continuous) CTD profiles with the reanalysis data at these three available depths – 200, 400 and 700 m. The main conclusion we made is that when constructing vertical temperature profile using reanalysis data it is better (better agreement with CTD) when we fixed temperature below 400 m rather than interpolate between 400 and 700 m. We added now a corresponding figure in the SI (Fig. S3) to make this part of discussion more clear.

p.8 l.23: This is also the case for Jakobshavn (figure 4).

Yes we agree that also Jakobshavn shows the same feature but this is shown in Figure 4. The actual location of the reanalysis point is only shown in Fig. 6 exemplary for Store Glacier. We therefore write now:

" Figure 4 and 5 compare the temperature at these depths from reanalysis data with available CTD profiles measured over past several decades for Jakobshavn-Isbrae and Store Glacier. Since Greenland is surrounded by the continental shelf with typical depths of 200–400 meters, most of the 700-meter depth grid-cells in the reanalysis data are located outside the shelves, far away from the glacier mouth as shown in Fig. 6 on the example of Store Glacier."

p.8 l.26-32: I have the impression (and this is not very clear in the manuscript) that *you don't use the sill depth in the fjords to determine the water properties in front of the glacier. The sills block the warm water at depth, which can significantly impact the water properties. This should be included for the plume model. Why not use that instead of an arbitrary depth of 400 m? Accurately including the fjord properties in important to separate the response due to the trend in climate changes from the impact of local conditions of the glaciers and the fjords.*

Again, we thank the reviewer for this suggestion. We demonstrate now (Fig. S3) that for temperature profiles derived from reanalysis data, changes according to a (shallow) sill depth do not improve the temperature profile in comparison to terminus-close CTD measurements. We therefore write: "Similar to the continental shelf, 'blocking' shallow sills in a fjords modify the water masses near the grounding line of a glacier. However, considering of the sill depth (Fig. S2, supporting information) when reconstructing the T-S profiles from the reanalysis data only leads to an even stronger temperature bias (dashed line Fig. S3, supporting information). Therefore, we always use the reanalysis data from 400m depth to construct T-S profiles irrespectively of the sill's depth" .

p.8 l.29: "larger" → "deeper"

Agreed, changed accordingly.

p.9 l.10: Again here, why used the temperature at 400 m depth and not the temperature at the grounding line depth? I think the value used should be designed to best represent the conditions in each and every fjord instead of using a generic value systematically applied to all the fjords.

Here we only derive a trend at the 400m depth point, from CMIP 5 models, since the continental shelf only allows water masses to pass from 0 to 400 m depth and the deep bottom water controls submarine melting. We add this trend to the total temperature profile (measured and reanalysis) which includes the temperature at the grounding line depth. We clarify now::"For future simulations, we prescribed simple scenarios for the ocean temperature anomalies based on temperature trends simulated by several CMIP5 models (GFDL-ESM2G, MPI-ESM-LR, and HadGEM2-CC). The trend is added to the T-S profiles (both CTD and reanalysis) for the future simulations. To determine this temperature trend we use the closest to the fjord model grid-cell with the depth larger than 400m for each CMIP5 model. The temperature trends were approximated by linear regression as illustrated in Fig. 8. The Figure shows as well, the big discrepancy between the model temperatures and CTD measurement at 700m depth which was the motivation to use 400 m depth only." this in the revised version.

p.9 l.16-21: It would be great to see the values of the different results, and especially how the different runs agree with the observations. More details on the choice of runs selected should also be added.

We demonstrate or results of the spin-up experiments of the present-day tuning in Figure 9. For completeness we now list the values of the 4 dynamical parameters, beta and fwd range and number of simulations in the SI Table S2 and S3 .

p.9 l.22-26: This paragraph is not clear.

Agreed. We would rewrite the paragraph to:

"Once the four dynamic parameters and the relaxation time scale are set in our precalibration, we performed a set of spin-up experiment with the coupled glacier-plume model for each glacier. In the spin-up experiments the submarine melt rate is now simulated interactively by the plume model which requires subglacial discharge and temperature and salinity profiles as inputdata. We used monthly subglacial discharge for the year 2000. Vertical temperature and salinity profiles in these experiments were taken from the reanalysis data, averaged over the time interval 1990–2010 or from recent CTD data, and were held constant in time (Fig. S3, supporting information). Nonetheless, in the spin-up experiments the submarine melt rate is not constant since changes in the grounding line depth and shape of a floating tongue (if exist) affect the submarine melt. We chose the year 2000 as the quasi-equilibrium initial state for "future" climate change simulations since the mass loss of GrIS during the last decade of 20the century was rather small (ca. 0.1

mm/yr in sea level equivalent) compare to that has been observed in the 21st century ((Vaughan et al., 2013)."

p.9 l.27: scaling of what? How is that done?

That was explained in 2.2 but we rewrite in brackets :" (factor in a range from 0.3 to 3 that multiplies the simulated melt rate profile)"

p.10 l.6: What is 3.3?

We forgot the word "section". Now inserted.

p.10 l.14-18: I think this could be easily simplifies in saying that you use the volume above flotation.

Agreed. We deleted the lengthy explanation with equations and added the sentence. "The contributing ice volume V_SLR is determined by the lost ice volume above flotation from each glacier"

p.10 l.21: Mention that is the present-day simulated state.

Done.

p.10 l.21: It is not clear what you mean by calving ratio.

We explain after the first occurrence: "(grounding line mass flux lost by submarine melting divided by mass loss of calving)"

p.10 l.23: The grounding line position is not clear on the figure, the ice front position is. Also most of these glaciers do not have any floating tongue, so it would be better to use the term ice front in this case.

We added a close-up view of the grounding line position in the SI (Fig. S5). Glaciers named as tidewater glaciers as e.g. Helheim still evolve small tongues mostly before the melt season. We added the sentence:

"Note that we allow for small floating termini, since many tidewater glaciers still evolve them on a seasonal scale and glacier fronts are also mostly undercut and thus missing a pure vertical cliff without any floating terminus (Bevan et al., 2012; Straneo et al., 2016; Rignot et al., 2015).

p.10 l.21-30: Do you actually want the glaciers to be stable or to be representative of the present-day conditions? Because many of these glaciers are losing mass and retreating today, so how much should a spin-up with present-day conditions lead to stable conditions?

See our response to the 3rd major comment

p.11 l.2: I thought that most of these glaciers did not have floating termini anymore!

We now address this issue by explaining why we allow for glacier tongues to evolve in our glacier model. (see answer o two comments above)

p.11 l.6 "by Enderlin .."

Adapted.

p.11 l.17: The numbers you provide do not include the present day changes? This is quite surprising and ends up presenting very low sea level change numbers that are not in good agreement with today's observations. It also questions the initialization procedure of the model, how much can we separate the present state and future changes given that the initial conditions have a lasting effect on the results.

We are not certain which numbers are meant here by the reviewer and how these numbers can be in agreement (or disagreement) with observations. In our paper we give only the contribution to SLR for the period 2000 – 2100. Our median estimate for the all Greenland glaciers based on upscaling is 50 mm, which is within the previous estimates for the same value. We argue that this number is complimentary to the SLR contribution simulated by a global GrIS model which does not account for ice sheet-ocean interaction (e.g. Calov et al., 2018). The sum of these two separate contributions (see our Discussion) gives ca. 140 mm, which is well within the range of existing estimates (e.g. IPCC, 2013; Fürst et al., 2015;). At the same time the recent estimates for the total GrIS contribution to SLR around the year 2000 is about 0.2-0.4 mm/a of which only half is attributed to the enhanced solid discharge (Enderlin et al., 2014). These numbers are not negligible but still significantly smaller than the average SLR which we simulated for the entire 21th century. Therefore the assumption we made that glaciers at 2000 were in quasi-equilibrium cannot have significant effect on our estimates for the SLR.

p.11 l.26: "excluding" → "separating"

Adapted accordingly.

p.11 l.27: This is not very clear, try to better separate the numbers for SMB only, elevation feedback, climate change trend, ocean, ... as is done in figure 11.

We write now:

"When forced by comprehensive climate change scenarios (changes in SMB with the surface elevation feedback, ocean temperature T and subglacial discharge Q) the median estimate for SLR contribution from all 12 glaciers is about 17 mm at the year 2100. To quantify the role of the individual forcing factors, we perform additional set of simulation with the model versions corresponding to the median SLR response by applying different forcing factors separately. We found that from the 17 mm over 70 % of SLR is caused by increased submarine melting due to the ocean warming T and increased subglacial discharge Q (Fig. 11 b). We found that both factors, T and Q, contributed an approximately equally to SLR. The reaming 30 % are attributed to the glacier's response to changes in SMB (Fig. 11 b, orange curve)."

p.11 l.30: "substantially" → "substantial"

Adapted accordingly.

p.12 l.13: The potential SLR and grounding line retreat are actually not listed in the tables.

We disagree, since they are listed in Table 3 and 4.

p.12 l.15: "uncertainties" → "spread"

Adapted accordingly.

p.12 l.18: There is only one model used to generate SMB, so where is the spread coming from? It is not clear if is caused only by the different initial conditions used or if here is something else. Also, why is there only one model used to generate SMB and several for the ocean?

The spread is actually coming from the different initial condition caused by the freshwater depth and beta. We inserted now this explanation " Since there is only one SMB forcing the spread originates from the different initial states cause by the different fwd and beta combination."

p.13 l.1: "1D line plume model" → "1D plume model" (same in other places in the manuscript). Also "Jenkins (2011)" → "(Jenkins, 2011)"

Adapted accordingly throughout the manuscript.

p.13 l.12: How does that compare to other 2D or 3D models of Jakobshavn [e.g., Muresan et al., 2016; Bondzio et al., 2017]?

We compare to other 3d simulations in our discussion:

"Simulated SLR contributions for the year 2100 compare well to values from Nick et al. (2013) for Jakobshavn Isbrae. The conservative estimations of Jakobshavn Isbrae contribution to SLR obtained with the 3D model of Bondzio et al. (2017) also lie within our uncertainty range. For the Kangerlussuaq Glacier our estimates for SLR contribution exceed estimation of Nick et al. by 2 mm, while for the Helheim Glacier our SLR estimations are below the estimation of Nick et al. (2013). In our simulations all glaciers experience a grounding line retreat which is found as well by Nick et al. (2013) but was not simulated by Peano et al. (2017). This discrepancy might be related to the coarse spatial resolution (5 km) of Peano et al. (2017) model (especially for the deep and narrow trough in Jakbobshavn) or processes upstream of the glacier might have counterbalanced the glacier retreat, which we could not simulate with a 1D flowline model."

p.13 l.19-20: remove

Adapted accordingly.

p.13 l.30-35: Use present tense instead of past tense.

Adapted accordingly.

p.14 l.5: What are the numbers for the entire Greenland if you only take the same glaciers as Nick et al. [2013]? How are these numbers impacted by the choice of glacier? So, if you only include a subset of the 10 glaciers used in this study, how does the sea level contribution of Greenland vary? It would be interesting to compute some kind of uncertainty associated with this method.

We thank the reviewer for this interesting suggestion and as mention above, we derived an uncertainty estimation by choosing 4 different glaciers in the SI.

p.14 l.7: "our our"

Deleted.

Fig.2: Is there a white dot in the fjord? It's not very clear. I don't understand the choice or the use of CTD profiles. Why not use all (or a combination of the different) profiles?

Since the plume equation require the temperature of the ambient water that entrains into the plume, we chose the closest, (and deep as the grounding line) avaible CTD measurement (closest to the glacier terminus) not CTDs far away. Fig. 2. was improved

"depth of 400 m" → "depth of at least 400 m". "od" → "of"

Adapted accordingly.

Fig.4: same as Fig.3

Yes, therefore we never use temperature profile from reanalysis data at 700m depth, since the are located outside the continental shelf.

Fig.6: It would be better to label all the dots (they are only 12). Again here, why use the depth-averaged temperature and not the temperature that most impact the plume model?

This was done to get a overview of how far the profiles of CTD and reanalysis data are actually of. We miss-wrote, since we actually show the temperature at the grounding line depth, which is the one that most impacts the plume model. We changed the axis-titles in Figure 6 and labeled all the dots, as suggested by the reviewer. Nevertheless, for transparency, we now show all the CTD an reanalysis data temperature profile for each glacier in the SI (Fig. S3).

Fig.8: Why present the results from only one ocean model and not from all of them?

Results of only one model and only for one location is shown in Fig. 8 just for illustration. The total range of temperature trends derived from different models and for different locations are given in Table S1, SI.

What is the implication of large discrepancy at 700 m depth between the model and the CTD measurement?

The likely reason for this discrepancy (actually 1°C error is not large for the GCMs) is that the nearest model grid point with the depth 700 m is located far from the CTD location. This is why, similarly to constructions of the vertical temperature profile from the reanalysis data, where the lowest depth we used was 400 m, to construct ocean warming scenarios we also disregarded levels below 400 m and instead prescribed temperature trend simulated by CMIP5 models at the depth 400 m. Note, that for climate change scenarios we did not use absolute values but only the anomalies simulated by CMIP5 models. These temperature trends for different locations and models are listed in table S1 (SI).

Fig.9: Is the observed bedrock directly taken from the BedMachine dataset along the centerline or is it representative of the entire glacier (of its entire width)? How many stable states are used for each glacier? I could not find this information in the manuscript.
And as mentioned above, do you really want the initial configuration to be stable or to represent the current state of the glacier? I am not sure "transparent lines" is the appropriate term.

We clarified the source from our bedrock. In part 3.2:
"We use the BedmACHInev2 data for bedrock topography (Morlighem et al., 2014). Fjord bathymetry was extended manually by considering available data (Mortensen et al., 2013; Schaffer et al., 2016; Dowdeswell et al., 2010; Syvitski et al., 1996; Rignot et al., 2016)." The number of stable states is listed in the table S1 in the SI.

Fig.10: "median-range3": repeat the superscript meaning here. Fig.11: "vom" → "from"

Done.

Fig.12: Try to use the same order as for Fig.11 for the lines. Fig.13: Would be better to repeat the entire caption.

Done.

Fig.14: What is "ocean temperature trend 1"?F

Listed in *Table* 1. Corrected in the revised version.

Tab.2: I thought that most glaciers in Greenland did not had floating termini any more,so why are there relatively large ratios of melting?

They do, within the season the can evolve short termini that are after the melt season mostly calved. We write:
" Note that we allow for small floating termini, since many tidewater glaciers still evolve them on a seasonal scale and glacier fronts are also mostly undercut and thus missing a pure vertical cliff without any floating terminus (Bevan et al., 2012; Straneo et al., 2016; Rignot et al., 2015)."

Tab.4: It is not clear what the sum of grounding line retreat represent. It is a rather unusual metric.

We agree with the reviewer and changed the entry in the table to the average grounding line retreat.

Response to reviewer 2

This paper investigates, by means of numerical modelling, the evolution of 12 outlet Greenland glaciers in the next century (2100). The employed numerical models are a 1D flowline glacier model and 1D (ocean) plume model, they are coupled together. Two aspects represent important limitations of this work: the use of a 1D glacier model for confined glaciers and the methodology followed in forcing and using the 1D coupled plume model. Some of the assumptions of this work are not properly addressed or discussed, as well as some of the consequences on the obtained results. This paper is clearly written, with the exception of some paragraphs that may lead to some confusion about the experimental setup (e.g. It is not clear if you actually run SICOPOLIS or not. Including a "methods section" may ease the reading).

We run SICOPOLIS and details to this can be found in our earlier study Calov et al 2018. All coauthors in this current paper contributed also to Calov et al. 2018. For this manuscript, only the output data on subglacial discharge from Calov et al 2018. were used to force the coupled glacier plume model.

Main comments

On the plume model:
I think that using the coupled 1D plume model is a great improvement. However some experimental choices limit the validity of this improvement.
At page 5 – line 2 is written that "since the plume model in some cases underestimate...
we also scale the simulated melt rate profile by a factor Beta...".
I have some comments on this: the relation between the plume forcings (temperature,salinity, shelf/tongue slope, subglacial discharge, . . .) and melt rate is given by robust physical equations (Jenkins, 2011; Beckmann et al. 2018). I believe that tuning the obtained melt rates with a multiplying factor waste all the efforts made in using (and coupling) the plume model. What is the need of this sophisticated model if then the computed melt rates are scaled to observed melt rates? Then why not using a simple depth dependent parameterization (e.g. Martin et al., 2011)?

Indeed, Jenkin's model of turbulent plume is based on the first principles and therefore it is expected it provides robust qualitative relationship between submarine melt ,ocean temperature and the slope of glacier front. Whether this model is also quantitatively correct for each Greenland fjord is another issue. The real world is very different from the assumptions behind the linear plume model since during summer season significant amount of melt water is delivered into the fjord through a number subglacial channels. . At present, there is no way to simulate realistically the large ensemble of different plumes, as well as many other processes (tidal circulation in the fjord, undercutting, etc) which may also contribute to submarine melt. To describe this complex reality we proposed to use the Jenkin's linear plume model but with additional correction by parameter beta. Obviously there is no prove that this parameter will stay constant for the next 100 years but still we believe that our approach represent an important improvement compare to a much simple parameterization (we assume that the reviewer means here the parameterization by Beckmann & Goosse, 2003) since we explicitly account for the dependence of submarine melt on subglacial discharge which is very important factor for the global warming simulations.

You tuned the computed plume melt rates on present day observed melt rates. How can you assume that this "present day" scaling will still be valid in 50/100 years? This choice is crucial in terms of providing a robust basal forcing for the glaciers evolution. I think that this assumption should be discussed.

As we explained above, there is no reason to expect that a very simple Jenkin's linear plume model can accurately described complex reality of Greenland fjords even at present and thus there is reason to expect that correction parameter beta will remain constant over 50 or 100 years. The reviewer is absolutely right (see Fig. 15): the choice of melt and calving parameters is the source of the largest uncertainties in glaciers contribution to future SLR and one of the aim of our paper is to report this problem. How to fix this problem is beyond the scope of this paper.

Given the inherent large uncertainties in forcing conditions (both in CTD and in re-analysis, page 8 line 3) what about forcing the plume model with a range of plausible temperature and salinity (from CTD and/or reanalysis) and with a range of subglacial discharges instead of tuning the computed melt rate?

Obviously, uncertainties in temperature profiles and subglacial discharge also contribute to the SLR uncertainties but very unlikely they contribute to the discrepancy between melt rate simulated by Jenkin's model an real one. Indeed, typical uncertainties in water temperature of 1°C will result in 20% uncertainties in melt rate. The uncertainties of 50% in subglacial discharge results only in 15% uncertainties in melt rate (due to cubic root dependence). At the same time, as we show in Beckmann et al (2018), melt rate simulated by linear plume model can deviate from observed one by factor 2-3.

It is not clear why you decide to use reanalysis data at 200, 400 and 700 meters of depth instead of using continous vertical profiles. Moreover, for future simulations you say: "...closest 400m-depth-point neighbor...". Is this motivated by line 29 to 31 at page C28? I understand this choice but I believe that you shold explain this better, clearly motivating also at page 9.

The first reviewer has a similar question which is addressed in our response. Note that we always use continuous profiles. Obviously, this part of our paper was not clear enough and imopoved it in the revised version.

On the glacier model:
I get why you decide to use a 1D flowline model: however I think that the limitations related to this approach (neglect of processes at the lateral boundaries and of buttressing, which play a crucial role in the evolution of ice masses) are not properly tackled and are mostly addressed by saying that 1D models are the only one available for this kind of study. This is probably right if you want to model 12 (or more) glaciers at the time, but for single glacier the last few years have seen important improvements in modelling alternatives that have produced results for some glaciers that are also modelled in this work (Chaulet et al., 2012; Seddik et al., 2012; Muresan et al., 2016; Peano et al.,2017; Goelzer et al., 2017). I think that the discussion about 1D model limitations should be expanded.

We agree with the reviewer and discussed more in depth the limitation of a 1D glacier model in the discussion part:
"Additionally, the 1D flowline model treat lateral processes in a simplified manner, so that more complex bedrock geometries (e.g. branching of glaciers, individual sills, unsymmetrical valley forms) are poorly represented in these estimations."

Also did introduce more work from other authors on 3d models on glaciers in the introduction part: "Peano et al. (2017) investigated the 5 biggest ice streams and outlet glaciers in Greenland with a 3D ice-sheet model on a resolution of 5 km. Seddik et al. (2012) and Gillet-Chaulet et al. (2012) included improved model physics by using a full-Stokes approach and refined resolution over fast flow regions with adaptive mesh techniques. Their setup however, did not yet allow to simulate glacier retreat. Most of the ice-sheet simulations also do not describe the interaction between glaciers and the ocean explicitly, but in some cases, for instance in Fürst et al. (2015), ocean melting is parameterized indirectly by increasing the basal sliding factor as ocean temperature increases. For the RCP scenario 8.5, they calculated a SLR between 155 and 166 mm at the year 2100 for the entire ice sheet atmospheric and oceanic forcing. For regional settings on 3D models with a simple ocean melting parameterization were applied to study the historical (last 20 -30 years) retreat of Jakobshaven Isbrae (Muresan and Khan, 2016; Bondzio et al., 2017). A more advanced treatment of submarine melt rate was done by Vallot et al. (2018).They coupled a plume model based on the Navier-Stokes equations with a full-Stokes ice sheet model. With this off-line coupling, glacier dynamics for one melt season were simulated for Kronebreen Glacier in Svalbard."

Specific comments

Page 1 – line 15: "factor analysis". With factor analysis it is usally meant a statistical method like the Empirical Orthogonal Functions (EOFs), in your work you just exclude
(one at the time) the different forcings, I would not strictly define this procedure as a factor analysis.

We changed “factor-analysis” to “ sensitivity analysis of the forcing-factors”.

Page 2 – line 5: instead of “global” I would use “atmospheric”
Adapted accordingly.

Page 2 – line 4 to 8: I found this paragraph ok, but I would rearrange it a little bit putting the described processes in the same order you are introducing them.
We now describe the processes in the order we introduce them.

Page 2 – line 6: “marine terminating” instead of “marine- terminating”
Adapted accordingly.

Page 2 – line 16: “In order to...” this should be a new paragraph
Adapted accordingly.

Page 2 – line 32: “that” is repeated two times
Deleted the second ‘that’.

Page 2 – line 35: “Since we are..” this should be a new paragraph
Insert a new paragraph.

Page 3 – line 1: I would say that the main (and only) improvement consists in using the coupled plume model. I consider the fact of studying more glaciers just as an “extension” of Nick et al. 2013 work.
Moreover, from the scaling perspective, are we sure that the considered glaciers are really representative of all the Greenland glaciers? especially given their variety in terms of glaciers and of confining fjords geometries/conditions.
Agreed, we changed the part to:, “...we followed an approach similar to Nick et al. (2013) but for different glacier-types and with one notable improvement.: For calculations of the vertically distributed submarine melt, we use a turbulent plume parameterization following Jenkins (2011).”

We considered 12 glaciers as in improvement compared to Nick et al. and selected them since they represent different ice flow regimes and different environmental conditions. We mention now that a sufficient sample size is crucial for the scaling method: “These resulting regression line is however not statistically significant. This underlines the importance of choosing a sufficiently large sample size.”

Page 3 – line 4: ok, but submarine melt rate depends also on the geometrical features of the tongue (shape, slope,…)

Agreed, we changed the sentence to. “According to this parameterization, the submarine melt rate depends not only on ambient water temperature in fjords but also on seasonally varying subglacial discharge, shape and angle of the glacier tongue.”

Page 3 – line 9 to 11: Maybe you can think about shortly describing how the scaling works.
Agreed we added: “In particular we derived a proportional factor between present-day grounding line discharge and future SLR using results of simulations for all twelve glaciers.”

Page 5 – line 1 to 5: I would expand the plume paragraph since it is the real innovative part of this study. Maybe a short introduction of the basic physics and equations. Otherwise is not clear what do you mean with the E entrainment parameter unless looking at Beckmann et al. (2018) (or already knowing what you are talking about).

We agree with the reviewer and extended now the whole paragraph and add the equation for the plume model.

Page 5 – line 17: "to the vertical mass balance term B", add the equation number

We added the equation number.

Page 5 – line 18 to 20: I imagine that when the plume detaches the melt rate is set to zero but this is not written explicitly. Is this the case?

We thank the reviewer for spotting the lack of information.
The plume never detaches from the glacier in the model, it only ceases by slowing down the velocity to zero. When this happens, the melt rate is set to a minimum melt rate to ensure background melting. We describe this in the revised version as the following: ". If the plume already ceases before reaching the calving front x_cf, we numerically introduce a minimal background melting determined by the last melt rate value before the plume ceased".

Page 5 – line 21: this part confused me. "...off-line using the ice sheet model" which one? This is the first time that you mention the use of an ice sheet model. Later it appears that it is SICOPOLIS.(see comment to page 6 – line 15 to 25)

Yes, we used SICOPOLIS output data which is described detailed in Carlov et al. 2018. We now write:
"We prescribe the subglacial discharge for each glacier simulated off-line with a monthly time step from the output of the ice sheet model SICOPOLIS."

Page 6 – line 1: "did we" "we did". Could you explain better in what this upscaling consists and how it works?

We added now we describe the upscaling method now firstly rough in the introduction part:
"In particular we derived a proportional factor between present-day grounding line discharge and future SLR using results of simulations for all twelve glaciers."

Page 6 – line 2: it would add more clarity defining what is meant with "melting to calving ratio"

Agreed, we inserted: "(grounding line mass flux lost by submarine melting divided by mass loss of calving)"

Page 6 – line 12: just a detail: I would number the figures in the order of appeareance in the manuscript.

Agreed, adapted accordingly.

Page 6 – line 15 to 25: From here it looks you actually run the ice sheet model, is this correct? (look comment to page 10 – line 6).I suggest to introduce explicitly the fact that you have run SICOPOLIS.

Yes, we run Sicopolis earlier and details can be found in Calov at el 2018. However, after the SICOPOLIS simulation we used the subglacial output data to force the coupled glacier plume model off-line. The sentence is changed to:
"The former two sources are computed directly from the ice sheet model SICOPOLIS by (Calov et al. 2018)."

Page 6 – line 23,24: "...is assigned to the closest glacier within a maximum of 50 km". This is an important approximation since is related to the plume forcing, however is not properly discussed, expecially in terms of uncertainty in the obtained results.

We now discuss: "This maximum distance is necessary in areas where only few named glacier positions are available (mostly in the South of Greenland) and the distance between glaciers is large. For most of the coastline, especially in the area of our selected glaciers, this distance has no effect on the results. We did not separately study the uncertainty in subglacial discharge related to this approach, but rather accounted for this uncertainty implicitly through the uncertainty of the scaling coefficient β for the submarine melt rate (see chapter 4.1)."

> *Page 6 – line 27,28: "neglect the effect of grounding line retreat".As above, this represents another important assumption but it is not properly discussed.*

True. We added :
"For neighboring glaciers with a competing catchment area, a strong ice sheet retreat may strongly affect the distribution of the subglacial discharge between those glaciers (Lindbäck et al., 2015). This effect is not included in this study."

> *Page 8 – line 12: "...presence of sills in the fjord...in the vicinity of the glacier front." I would explain why is that after this line, instead than explaining it later for the continental shelf (at page 8 – line 24 to 30).*

We rearranged the whole sub-chapter on temperature and salinity profiles.

> *Page 9 – line 16: could you provide a table with the prescribed submarine melt rate and the range of values for the dynamic parameters? (maybe in the supplementary)*

Agreed, we provided it int the table S1 in the SI.

> *Page 9 – line 25: with "...only factors.." do you mean that since temperature and salinity are "held constant" (thus not changing) their contribution in impacting melt rates is constant in comparison to the impacts due to a varying grounding line depth and tongue shape/slope? I suggest to reformulate this paragraph*

Yes, we just wanted to point out that although the temperature-salinity profile is held constant the melt rate isn't necessarily constant due to the glacier's changing geometry. We now write "Nonetheless, in the spin-up experiments, the submarine melt rate isn't necessarily constant since changes in the grounding line depth and shape of a floating tongue (if exists) affect the plume equations. "

> *Page 9 – line 29 "...is close to equilibrium state.." what do you mean with equilibrium?*
> *Later you speak about stable state. Do you mean steady? I would argue that currently Greenland glaciers are definitely not in a steady condition.*

The same issue was addressed by reviewer 1 (major comments) and we defined our definition on the present-state (2010) more clearly.

> *Page 10 – line 5: "...each glacier 3.4..." something is missing between glacier and 3.4*

Delete 3.4. (typo).

> *Page 10 – line 6: "...glacier individually 3.3..." something is missing between individually and 3.3*

We thank the reviewer for spotting the mistake we insert the word "section".

> *Page 10 – line 6: Here it is not clear if you took the data from Calov et al. 2018 or if you actually run the model*

This paper and Calov et al. (2018) are closely related. They originate from the same project and are written essentially by the same group of authors. Calov et al. (2018) describes the model of Greenland glacier system, experimental setup and results of several climate change experiments.

In Calov et al. (section 5) we also described how we computed time-dependent subglacial discharge for individual Greenland glaciers using SICOPOLIS and MAR output, and the basal hydrology model HYDRO. In the current work, we used this time-dependent discharge as the forcing for modeling of 12 selected glaciers. We clarified this issue in the revised manuscript.

> *Page 10 – line 22,24: this part about the interplay between melting, calving and bedrock is interesting. I would add few more details.*

We now broaden the discussion and write:
"We found that for some glaciers, the grounding line demonstrates a high sensitivity to the melting/calving ratio, while others are primarily controlled by their bedrock topography and have relatively small variations in their grounding line position over the whole melting/calving ratio range. The Gade and Upernavik North glaciers are examples of the latter case (Fig. S6, supporting information). In general, we observed higher velocities at the glacier terminus when higher calving rates were applied. Thus, if a glacier is not strongly buttressed by a sill or lateral resistance, different values of velocity at the glacier terminus due to different d w strongly affect the equilibrium grounding line position. Such behavior points on the crucial role of the bedrock topography for glacier dynamics."

> *Page 11 – line 6: a space is missing before "Enderlin"*

Insert space.

> *Page 11 – line 15: "model versions" do you mean the the spin-up ensemble?*

Yes, we now write.:"After obtaining the present-day state, we then ran the model ensemble with all valid beta/fwd combination ..."

> *Page 11 – line 16: why not changing also the subglacial discharge? It is such an important forcing for the plume and comes from several approximations (fixed grounding line and closest neighboring approach).*

We fully agree with the reviewer that in this study we explore only a fraction of uncertainty sources. In particular subglacial discharge as well as SMB also depends on the choice of the regional climate model and the global climate models which has been used to provide boundary conditions for the regional model. However, we believe that Fig. 15 already provides a very important inside into the major source of uncertainties in simulated glaciers contribution to SLR. Namely, it shows that the uncertainties in the choice of model parameters is likely to be the largest source of the SLR uncertainty. Thus to considerably narrow down these uncertainties, the glacier model parameters have to be better constrained.

> *Page 11 – line 17: at page 10 (line 8 to 10) is said that also the unforced model drift is calculated. Then this drift is removed by subtracting it from calculated values. This implies that a linear behaviour for glaciers is assumed. I think that this should be properly discussed.*

Of course it is known that glaciers response to climate change is nonlinear and we do not assume such linearity. Our modeling approach is based on the assumption that glaciers were in equilibrium at the year 2000. However, to ensure that all glaciers are in the perfect equilibrium with the 2000 year forcing would be required to perform infinitive number of infinitively long spin-up experiments which is not possible even with fast model. This is why we apply as additional constrain, namely, we excluded all model realizations with positive (mass gain) trend and require that the simulated negative trend is significantly smaller than simulated SLR response to climate change scenario. Still, we have to tolerate non-negligible drift in the control runs - otherwise we will be left with to few accepted model realizations. This is why we decided to exclude such drift from the forced run which we believe is still better to do it. We included now:
"All results shown here have a small model drift subtracted from the calculated values, to ensure that the simulated SLR is a response to the climate change."

> *Page 11 – line 25-27: as above, this implies linearity but glaciers are definitely not*

linear systems. This issue is just slightly addressed at page 12 – line 4.

We did not assume that glaciers are linear systems. As we explained in the response to the first reviewer, the drift is rather small since we only accepted such model versions in which drift is smaller than simulated SLR in the forced experiments. Of course, zero drift in unforced experiment would be preferable, but this cannot be achieved with the finite computational resources. Therefore we are left with two to options: (i) to leave forced experiments as they are or (i) to exclude unforced drift from the forced experiments. Both options are imperfect but we prefer the second one.

21,22: you attribute the source of uncertainty to Beta, this comes from the fact that Beta is responsible for the imposed melt rate (through the tuning procedure). However Beta is just a model parameter, I think that avoiding the use of Beta (as suggested in he main comments) could also improve this part of the work, it will allow you to relate uncertainties to physical quantities.

As we explained above, there is no physical reasons why the linear plume model should produce correct results with beta=1. See also Beckmann et al. (2018).

Page 13 – line 18 to 20: something is wrong here, an entire sentence is repeated.

The repetition was deleted.

Page 13 – line 33: same as above. Your results are not affected by CTD/reanalysys temperature and salinity because the Beta tuning incorporates all the uncertainties.

We agree with the reviewer that colder temperatures in the reanalysis data set in some (but not all cases) can be balanced by a higher beta. We provided the new table showing which beta values were used for CTD and reanalysis data set in the supporting information (Tab. S3)

Page 13 – line 35: "...observational constraints on submarine melt..." as explained in the main comments I think that we should rely on melting formulation as less as possible dependent from a tuning on observations, especially for future projections.

We agree that this would be a nice idea but not at the present level of ice sheet-ocean interaction. As we showed in Beckmann et al 2018, Jenkin's linear plume model does not produce observed submarine melt and therefore should be corrected. Even with this correction believe that our approach is more physically based and therefore more trustworthy than those used in previous studies.

Page 14 – line 4: "and" repeated two times

Deleted.

Page 14 – line 7: "our" repeated two times

Deleted.

Figure 3(a): I think that using white dots is a bit unfortunate, also the red star is not very visible.

Agreed, we improved Figure 3 for more visible CTD location.

Figure 11: "from" instead of "vom"

Adapted accordingly.

Modeling the response of Greenland outlet glaciers to global warming using a coupled flowline-plume model

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Abstract.

In recent decades, the Greenland Ice Sheet has experienced an accelerated mass loss, contributing to approximately 25 % of contemporary sea level rise. This mass loss is caused by increased surface melt over a large area of the ice sheet and by the thinning, retreat and acceleration of numerous Greenland outlet glaciers. The latter is likely connected to enhanced submarine melting that, in turn, can be explained by ocean warming and enhanced subglacial discharge. The mechanisms involved in submarine melting are not yet fully understood and are only ~~crudely~~ simplistically incorporated in some models of the Greenland Ice Sheet. Here, we investigate the response of twelve representative Greenland outlet glaciers to atmospheric and oceanic warming using a coupled ~~1D~~ line-plume glacier-flowline model resolving one horizontal dimension. The model parameters have been tuned for individual outlet glaciers using present-day observational constraints. We then run the model from present to the year 2100, forcing the model with changes in surface mass balance and surface runoff from simulations with a regional climate model for the RCP 8.5 scenario, and applying a linear ocean temperature warming with different rates of changes representing uncertainties in the ~~CMIP 5~~ CMIP5 model experiments for the same climate change scenario. We also ~~used~~ use different initial temperature-salinity profiles obtained from direct measurements and from ocean reanalysis data. Using different combinations of submarine melting and calving parameters that reproduce the present-day state of the glaciers, we ~~estimated~~ estimate uncertainties in the contribution to global sea level rise for individual glaciers. We also ~~performed a factor analysis~~ perform a sensitivity analysis of the forcing-factors, which shows that the role of different forcing (change in surface mass balance, ocean temperature and subglacial discharge) are diverse for individual glaciers. We ~~found~~ find that changes in ~~,~~ ocean temperature and subglacial discharge are of comparable importance for the cumulative contribution of all twelve glaciers to global sea level rise in the 21st century. The median range of the cumulative contribution to the global sea level rise for all twelve glaciers is about ~~14~~ 17 mm from which roughly ~~85~~70 % are associated with the response to increased submarine melting and the remaining part to surface mass loss. We also ~~found a weak~~ find a strong correlation (correlation coefficient ~~0.35~~0.75) between present-day grounding line discharge and their future contribution to sea level rise in 2100. If the contribution of the twelve glaciers is scaled up to the total present-day discharge of Greenland, we estimate the mid-range contribution of all Greenland glaciers to 21st-century sea level rise to be approximately 50mm. This number adds to SLR derived from a stand-alone, coarse resolution ice sheet model and thus increases SLR by over 50 ~~mm~~%. This result confirms

earlier studies that the response of the outlet glaciers to global warming has to be taken into account to correctly assess the total contribution of Greenland to sea level change.

1 Introduction

Sea level rise (SLR) is one of the major threats to humanity under global warming, and approximately one-fourth of the recent SLR can be attributed to the Greenland Ice Sheet (GrIS) (Chen et al., 2017). In the future projections of SLR, the GrIS is not only one of the major potential contributors but also a significant source of uncertainty. Two processes are largely responsible for the GrIS contribution to SLR: (1) ~~increased surface melt induced by global warming and (2)~~ dynamic mass loss due to retreat and acceleration of outlet glaciers ~~(Khan et al., 2014). The latter,~~ (40 %) and (2) increased surface melt induced by atmospheric warming (60 %) (Khan et al., 2014; Van Den Broeke et al., 2016). The first process which is most pronounced for ~~marine-~~ marine terminating outlet glaciers (Moon et al., 2012), is potentially caused by an increase in submarine melting, which can in turn be attributed to a warming of the ~~ocean~~ subpolar North Atlantic ocean, induced by circulation changes, and increased subglacial discharge (Straneo and Heimbach, 2013). Regarding the ~~first~~ latter mechanism, the maximum contribution due to increased surface melt is estimated to range between ~~0~~ 50 to 130 mm by the year 2100 (Fettweis et al., 2013). Due to the possibility of applying relatively high-resolution regional climate models, confidence in this estimate has increased in the recent years (van den Broeke et al., 2017). The contribution of the second process remains highly uncertain because processes related to the response of ~~marine-terminated~~ marine terminated Greenland glaciers are still not properly represented in the contemporary GrIS models ~~(Straneo and Heimbach, 2013)~~(Straneo and Heimbach, 2013; Khan et al., 2014; Goelzer et al., 2017) .

The principal objective of this paper is to quantify the response of ~~marine-terminating~~ marine terminating outlet glaciers to future submarine melting and to analyze whether the impacts of ice-ocean interaction on SLR are comparable to long-term changes in surface mass balance (SMB).

In order to assess Greenland's contribution to future sea level rise, several different model strategies have been proposed. The most common method is to use three-dimensional ice sheet models, tuned to present-day conditions, and apply future climate change projections based on global or regional climate models. However, such models still have relatively coarse spatial resolution and cannot properly resolve most of the outlet glaciers that terminate in Greenland's fjords. ~~They~~ Peano et al. (2017) investigated the 5 biggest ice streams and outlet glaciers in Greenland with a 3D ice-sheet model on a resolution of 5 km. Seddik et al. (2012) and Gillet-Chaulet et al. (2012) included improved model physics by using a full-Stokes approach and refined resolution over fast flow regions with adaptive mesh techniques. Their setup however, did not yet allow to simulate glacier retreat. Most of the ice-sheet simulations also do not describe the interaction between glaciers and the ocean explicitly, but in some cases, for instance in Fürst et al. (2015), ocean melting is parameterized indirectly by increasing the basal sliding factor as ocean temperature increases. For the RCP scenario 8.5, they calculated a SLR between 155 and 166 mm at the year 2100 for the entire ice sheet atmospheric and oceanic forcing. For regional settings, 3D models with a simple ocean melting parameterization were applied to study the historical (last 20 -30 years) retreat of Jakobshaven

Isbrae (Muresan and Khan, 2016; Bondzio et al., 2017). A more advanced treatment of submarine melt rate was done by Vallot et al. (2018).They coupled a plume model based on the Navier-Stokes equations with a full-Stokes ice sheet model. With this off-line coupling, glacier dynamics for one melt season were simulated for Kronebreen Glacier in Svalbard.

Another method, followed by Nick et al. (2013), is to simulate single outlet glaciers individually using a ~~1-dimensional~~ one-dimensional (1D) flowline model. Nick et al. (2013) performed simulations for four outlet glaciers that collectively drain about 22 % of the total solid ice discharge of the Greenland Ice Sheet. Assuming proportionality between the future contribution to SLR and present-day ice discharge, Nick et al. (2013) scaled up results obtained from four glaciers to the total estimate of all Greenland outlet glaciers, which resulted in a range between 65 and 183 mm by the year 2100. Taking this one step further, Goelzer et al. (2013) used the results from Nick et al. (2013) in a 3D coarse-resolution ice sheet model. They applied the 1D glacier thinning and grounding-line retreat scenarios as an external, pre-calculated forcing in the grid cells at the ice sheet boundary. Since only four glaciers had been simulated in the 1D model, they mapped the forcing from the original glaciers onto all other Greenland's ~~marine-terminating~~ marine terminating outlet glaciers with a nearest neighbour approach. The incorporation added only 8 to 18 mm SLR on top of the stand-alone 3D ice sheet model simulation. Goelzer et al. (2013) argued~~that~~, that the smaller contribution results from smaller ~~marine-terminating~~ marine terminating glacier that fully retreat in the 3D ice simulations, leaving no more ice-ocean, which is still included by the upscaling from Nick et al. (2013).

Since we are especially interested in the impacts of ice-ocean interactions on glacier dynamics and want to investigate numerous glaciers, we followed an approach similar to Nick et al. (2013) but ~~with several notable improvements.Firstly, for~~ for different glacier-types and with one notable improvement.: For calculations of the vertically distributed submarine melt, we ~~used~~ use a turbulent plume parameterization following Jenkins (2011). According to this parameterization, the submarine melt rate depends not only on ambient water temperature in fjords but also on seasonally varying subglacial discharge, shape and angle of the glacier tongue. The first idealized simulations of a coupled flowline-plume model were carried out by Amundson and Carroll (2018) by using the maximum melt rate as a frontal ablation factor to account for undercutting plus calving of tidewater glaciers , demonstrating the potential impact of the subglacial discharge on glacier dynamics. For the evolution of the surface mass balance, we used anomalies computed by the regional climate model MAR and corrected them for surface elevation change.~~Finally, we performed~~

We perform simulations for 12 representative Greenland glaciers (compared to four in Nick et al. (2013)). This enabled us to test the assumption used in Nick et al. (2013) that the contribution of individual Greenland outlet glaciers to SLR is proportional to their present-day discharge and therefore the total contribution of Greenland outlet glaciers can be obtained by scaling up contribution of individual glaciers proportionally to the entire present-day discharge of all outlet glaciers. In particular we derived a proportional factor between present-day grounding line discharge and future SLR using results of simulations for all twelve glaciers. We also estimated the uncertainties in the contribution of Greenland glaciers to SLR resulting from uncertainties in calving and ocean melt parameters and climate change scenarios.

The paper is structured as follows. First, we describe the coupled flowline-plume model, then how the input data were preprocessed together with the experimental setting and climate change scenarios. Finally, we present the results of our model simulations for present day and future scenarios.

2 The coupled flowline-plume model

Most of Greenland's outlet glaciers terminate in fjords that are connected to the ocean. Inside these fjords, observations of upwelling plumes along the edges of glaciers have drawn attention to the importance of submarine melting. Consequently, considerable efforts in modeling of submarine melt rate have been undertaken by using high-resolution 3D and 2D ocean general circulation models that are tuned to or parameterized after the buoyant-plume theory (Sciascia et al., 2013; Xu et al., 2013; Slater et al., 2015; Cowton et al., 2015; Carroll et al., 2015; Slater et al., 2017). However, such models are too computationally expensive and therefore impractical for simulating the response of the entire GrIS to climate change on centennial timescales. At the same time, recent studies demonstrate that the simple line plume model by Jenkins (2011) is an adequate tool to simulate plume behavior (Jackson et al., 2017) and to determine submarine melt rates for ~~marine-terminated~~ marine terminated glaciers (Beckmann et al., 2018). Since the plume model is significantly less computationally expensive than 3D ocean models, it represents an alternative approach to introduce ice-ocean interaction into the GrIS model and still maintain the model's ability to perform a large set of centennial-scale experiments. Simulating the glacier dynamics with 3D ice sheet ~~model~~ models requires very high spatial resolution ($\ll 1$ km) resulting in high computational cost (e. g. Aschwanden et al., 2016) and so far they cannot be used for centennial timescales. To reduce the computational cost we ~~used~~ use instead a 1D depth- and width- integrated one-dimensional ice flow model (Enderlin and Howat, 2013; Nick et al., 2013) coupled to a line plume model (Beckmann et al., 2018).

2.1 Glacier model

The governing equations of the 1D model include mass conservation:

$$\frac{\partial H}{\partial t} = -\frac{1}{W}\frac{\partial (UHW)}{\partial x} + \cancel{B}\dot{B} - \dot{M}, \tag{1}$$

where H is ice thickness, t is time, U is the vertically averaged horizontal ice velocity, W is the width and x is the distance from the ice divide along the central flowline. ~~B is the sum of SMB and submarine melting~~Where $\dot{B}$ and $\dot{M}$ are the surface mass balance and the submarine melt rate of one glacier.

The conservation of momentum involves a balance between longitudinal stress, basal shear stress and lateral stress on the one hand, and driving stress on the other:

$$2\frac{\partial}{\partial x}\left(H\nu\frac{\partial U}{\partial x}\right) - A_s\left[(H - \frac{\rho_w}{\rho_i}\cancel{D}h_b)U\right]^q - \frac{2H}{W}\left(\frac{5U}{EAWW_s}\right)^{\frac{1}{3}} = \rho_i g H\frac{\partial h_s}{\partial x}, \tag{2}$$

where h_s denotes the ice surface height, ~~D~~ h_b the depth of glacier below sea-level, ρ_i and ρ_w the ice and sea water density, respectively. ~~Basal stress is parameterized~~ The sliding law follows Nick et al. (2010) with the basal sliding coefficient A_s and the velocity exponent q~~and~~, and the lateral stress involves a ~~nondimensional~~ non-dimensional width-scaling parameter W_s. The lateral stress term likewise used by e.g. Nick et al. (2013); Enderlin and Howat (2013); Schoof et al. (2017), and originally derived by Van Der Veen and Whillans (1996), is necessary to account for lateral resistance in fast-flowing, laterally-confined glaciers typical for Greenland. Finally, the rate factor A and the enhancement factor E determine the viscosity ν

$$\nu = (EA)^{\frac{1}{3}} \left| \frac{\partial U}{\partial x} \right|^{-\frac{2}{3}}. \tag{3}$$

Calving occurs when surface crevasses propagate ~~until~~ down to the water level (Nick et al., 2013). Crevasses depth d_s is calculated from the resistive stress $R_{xx} = 2\left(\frac{1}{A}\frac{\partial U}{\partial x}\right)^{1/3}$, as ice stretches, and can be enhanced by ~~melt water~~ freshwater depth d_w:

$$d_s = \frac{R_{xx}}{\rho_i g} + d_w \frac{\rho_0}{\rho_i} \tag{4}$$

where ρ_0 is the freshwater density. The glacier front continuously advances over time, as the accumulated flux leaving the last grid cell is recorded and the calving front is advanced whenever the accumulated volume reaches the volume of a grid cell (assuming same thickness). Glacier front advance and calving are the two competing processes that determine the calving front position.

Initial boundary condition is U(x=0) = 0, while at the calving front ~~, we use~~ x_{cf} balancing the longitudinal stress with the hydrostatic sea water pressure and incorporating the flow law of ice yields longitudinal stretching

$$\frac{dU}{dx} \left.\frac{\partial U}{\partial x}\right|_{x=x_{cf}} = EA\left[\frac{\rho_i g H}{4}\left(1 - \frac{\rho_i}{\rho_w}\right)\right]^3. \tag{5}$$

The model employs a stretched horizontal grid with a horizontal resolution of 100 meters, where velocity is calculated at mid-points. At each time step of 3.65 days, the grid is stretched to keep track of the grounding line position, which is determined by the flotation criterion

$$H_{\text{float}} \le |z_b| \frac{\rho_{\text{w}}}{\rho_i}, \tag{6}$$

where z_b is the bedrock depth. Glacier thickness H and bedrock depth z_b of each cell interface are determined by linear interpolation between the cell centered values. Grid stretching is performed so that there is always a cell edge at the interpolated grounding line position. The new calving front position is determined so that the total glacier volume is not modified by interpolation. For every new point in the interior, model variables are interpolated from previous grid. The first grid point at the ice divide remains unchanged. If ice grid points on the new grid lie outside the ice domain on the previous grid, as it is typically the case for the last cell before the calving front, ice thickness from the last grid cell is extended.

The code is written is ~~fortran~~FORTRAN, following the numerical procedure of Enderlin et al. (2013). The main differences compared to their original matlab code[1] is that we include a subgrid-scale treatment of the calving front boundary, and an improved treatment of the submarine melting.

2.2 Plume model

The plume model equations ~~are described in Beckmann et al. (2018)~~account for a uniformly distributed subglacial discharge along the grounding line of a glacier , and contain the the evolution of the plume thickness D, velocity V, temperature T and salinity S along the direction of the plume.

[1] available at https://sites.google.com/site/ellynenderlin/research

$$q_s' = \dot{e} + \dot{m} \tag{7}$$

$$(q_s V)' = D\frac{\Delta\rho}{\rho_0} g \sin(\alpha) - C_d V^2 \tag{8}$$

$$(q_s T)' = \dot{e} T_a + \dot{m} T_b - C_d^{\frac{1}{2}} V \Gamma_T (T - T_b) \tag{9}$$

$$(q_s S)' = \dot{e} S_a + \dot{m} S_b - C_d^{\frac{1}{2}} V \Gamma_S (S - S_b) \tag{10}$$

The volume flux of the plume $q_s = DU$ (expressed per unit length in the lateral direction, i.e. $\mathrm{m^2 s^{-1}}$) of the plume is described by equation (7). It can increase by the entrainment of ambient seawater $\dot{e}$ and by melting $\dot{m}$ of ice from the glacier front. Equation (Eq. 8) describes the balance between buoyancy flux and the drag $C_d U^2$ of the glacier front. The buoyancy flux is proportional to the relative density contrast $\frac{\Delta\rho}{\rho_0}$ between plume water and ambient water in the fjord (subscript a). This density contrast is linear parameterized as $\beta_S(S_a - S) - \beta_T(T_a - T)$. The drag also results in a turbulent boundary layer (subscript b) at the ice-water interface, where melting occurs, and heat and salt is exchanged by (turbulent) conduction-diffusion. The temperature T and salinity S of the plume (Eq. 9,10) are determined by the entrainment of ambient water and the addition of meltwater, as well as by conduction fluxes at the ice-water interface (i.e. between boundary layer and plume). The entrainment rate is calculated as $\dot{e} = E_0 U \sin(\alpha)$, proportional to plume velocity and glacier slope, with the entrainment coefficient E_0.

The submarine melt rate along the path of the plume $\dot{m}$ is determined by solving the equations of heat and salt conservation at the ice-water interface:

$$\dot{m}L + \dot{m}c_i(T_b - T_i) = cC_d^{\frac{1}{2}} V \Gamma_T (T - T_b) \tag{11}$$

$$\dot{m}(S_b - S_i) = C_d^{\frac{1}{2}} V \Gamma_S (S - S_b) \tag{12}$$

where T_i and S_i, c_i are the temperature, salinity and the specific heat capacity of the ice and c the specific heat density for sea water. At the ice water interface the freezing temperature T_b is approximated as a linear function of depth Z ($Z < 0$) and salinity of the boundary layer S_b:

$$T_b = \lambda_1 S_b + \lambda_2 + \lambda_3 Z \tag{13}$$

with $Z = Z_0 + x \cdot \sin(\alpha)$, where Z_0 is the depth (negative) at the grounding line ($x = 0$). The algorithm for solving the set of equations and a list of all parameter values are provided in Beckmann et al. (2018).

We set the entrainment parameter E to 0.036, as suggested by Beckmann et al. (2018)~~,~~ . Since the plume model in some cases underestimates and in others overestimates submarine melt rates (Beckmann et al., 2018), we also scale the simulated melt rate profile by a constant factor β, which we treat as ~~a~~ an additional tuning parameter within the range 0.3 - 3 (see section 4.1). The plume model employs a ~~finer~~ fine spatial resolution of ~~<~~ about 1 m.

2.3 Coupling between glacier and plume model

Unlike Amundson and Carroll (2018), who used the maximum melt rate as a frontal ablation factor for tidewater glaciers, we take into account the entire ~~vertical melt rate profile calculated~~ profile along the submerged part of the outlet glacier to calculate the submarine melt rate with the plume model. Submarine melting volume flux is calculated for each cell and is applied as a vertical thinning rate on the floating tongue ($x_{g+1}...x_c$), or on the last grounded cell (x_g) in the case of tidewater glaciers (no floating tongue). The melt rate ~~m~~ $\dot{m}$ is integrated from the grounding line (position x_{gl}) along the bottom face of the floating tongue (if any), and along the calving face (position x_{cf}) up to sea level (Fig. 1), or to the top height of the risen plume (which can stop ~~before~~ below sea level). The ~~cumulative melt rate~~ total submarine melt rate over the glacier tongue (if any) for one outlet glacier is given by

$$M = \int \dot{m}(s)\, ds = \int\limits_{x_{gl}}^{x_{cf}} \dot{m}(h_b(x)) \cdot (\cos\alpha)^{-1} dx + \int\limits_{h_b(x_{cf})}^{0} \dot{m}(z) dz, \tag{14}$$

where s is the distance coordinate along the tongue bottom and the vertical calving face, h_b denotes bottom ice elevation, and ~~$cos\alpha$~~ $\cos\alpha$ is the variable tongue slope (calculated from the relation $\tan\alpha = \frac{\partial h_b}{\partial x}$). The integral is ~~distributed over various~~ partitioned over various glacier cells (or only one cell (x_g) in the case of a tidewater glacier, where the first integral term is ~~also~~ zero since $x_{gl} = x_{cf}$)~~, and the volume flux is added to the vertical mass balance term B, along with surface mass balance.~~ . This total submarine melt rate, in a cell by cell basis, is substituted in (the discrete form) of equation (1):

$$M_i = \int\limits_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \dot{m}(s)\, ds + \varepsilon_i \int\limits_{h_b(x_{cf})}^{0} \dot{m}(z) dz, \tag{15}$$

where ε_i is 1 if i represents the last ice cell ($x_i = x_c$), or 0 otherwise. The submarine melt rate $\dot{M}$ per units of length for each glacier cell (dx) in Eq. 1 is

$$\dot{M}_i = \frac{M_i}{dx} \tag{16}$$

. If there is no floating tongue, submarine melting is applied to the last grounded cell, otherwise it is applied starting from the first floating cell.

Thus the submarine melt rate reduces the thickness of the glacier cell. A reduced thickness at the first floating cell or last grounded cell leads to grounding line retreat since the grounding line position is determined by interpolation of the ice thickness above flotation at each time step. Thinning the last floating cell leads to calving front retreat by either melting the total cell or by calving, which increases with thinning.

Since the plume model does not allow for negative values of α, its minimum value is set to 10^{-6}. If the plume already ceases before reaching the calving front x_{cf}, we numerically introduce a minimal background melting determined by the last melt rate value before the plume ceased. At the calving front we calculate a 2nd plume that starts at $\cancel{h_b(x_cf)}$ $h_b(x_{cf})$ with the initial minimum default discharge value of $\cancel{10^{-6}m^3s^{-1}}$ 10^{-6} m^3 s^{-1} to assure a background frontal melting.

Subglacial discharge Q for each glacier was computed off-line ~~using the~~ from the output of simulations with the ice sheet model ~~with~~ SICOPOLIS (Calov et al., 2018) which includes explicit treatment of basal hydrology (Section 3.3)~~, then~~. It is applied to the line plume~~in distributed form~~ $\cancel{q = Q(W)^{-1}}$, assuming a uniform distribution of subglacial discharge along the width of the grounding line: $q_s = Q(W)^{-1}$. It is assumed that plume properties (velocity, temperature, salinity, and thickness) ~~in the coupled model~~ adapt instantaneously to changes in the glacier's shape, subglacial discharge, temperature and salinity profiles of ambient water. The glacier and plume model exchange information at every time step of the glacier model.

3 Model Input

3.1 The choice of glaciers

In this study, we modeled twelve, well-studied Greenland outlet glaciers of different sizes and located in different regions of Greenland (Fig. 2). One criterion ~~of~~ for this selection is that the glaciers should represent different types of ice flows and different environmental conditions. ~~Also, did we include small marine-terminating~~ We also include small marine terminating glaciers to assure a more realistic upscaling ~~as Goelzer et al. (2013)indicates~~Goelzer et al. (2013). Besides that, for most of the chosen glaciers, Enderlin and Howat (2013) estimated submarine melting to calving ~~ratio~~ ratios (grounding line mass flux lost by submarine melting divided by mass loss of calving) which we use as an additional constraint on the choice of modeling parameters.

3.2 Glacier geometry

For each individual glacier, bedrock elevation and width were determined by analyzing cross-sections taken at regular intervals along the glacier flow, generally covering a large portion of the glacier catchment area (Perrette et al., in prep). In each cross-section, the procedure comes down to calculating a flux-weighted average for bedrock elevation, ice velocity U and thickness H, and choose the glacier width W such that the flux F through the cross-section is conserved, i.e. $W = F/(UH)$ ~~(Perrette et al. , in prep).~~. We use the BedmACHInev2 data for bedrock topography (Morlighem et al., 2014). Fjord bathymetry was extended manually by considering available data (Mortensen et al., 2013; Schaffer et al., 2016; Dowdeswell et al., 2010; Syvitski et al., 1996; Rignot et al., 2016). For ice velocity we use data from Rignot and Mouginot (2012). The resulting glacier profiles are depicted in ~~Fig. 9.~~ Fig. 9.

3.3 Subglacial discharge and glacier surface mass balance

To force the plume model, we use monthly averaged subglacial discharge. Subglacial discharge represents the sum of basal melt (melt under the grounded ice sheet), water drainage from the temperate layer and surface runoff. The former two sources are computed directly ~~in~~ by the ice sheet model ~~(Calov et al. 2018).~~ SICOPOLIS (Calov et al., 2018). In reality surface runoff can travel along the ice surface until it either reaches an existing connection to the bedrock (e.g. crack) or it accumulates in a supraglacial lake that eventually drains, making a new connection. However, these processes are too complex and still poorly understood. This is why in ~~our~~ the relatively coarse (5 km) resolution ice sheet model (Calov et al., 2018), ~~we neglect these short scale processes and assume~~ these small-scale processes are neglected and it is assumed that runoff penetrates directly down to the bedrock. The surface runoff and SMB anomalies for ~~present day and~~ future scenarios are taken from experiments with the regional climate model MAR (Fettweis et al., 2013) and corrected for the future surface elevation change (Calov et al., 2018). The entire ~~water~~ basal water flux (runoff, basal melt, and water from the temperate layer) is routed by the hydraulic potential using a multi-flow direction flux routing algorithm, as described in (Calov et al., 2018). All water transfer is assumed to be instantaneous. Water that passes ~~the grounding line (defined by the ice mask from SICOPOLIS)~~ through the boundary of prescribed SICOPOLIS ice mask is assigned to the closest glacier within a maximum distance of 50 km. This maximum distance is necessary in areas where only few named glacier positions are available (mostly in the South of Greenland) and the distance between glaciers is large. For most of the coastline, especially in the area of our selected glaciers, this distance has no effect on the results. We did not separately study the uncertainty in subglacial discharge related to this approach, but rather accounted for this uncertainty implicitly through the uncertainty of the scaling coefficient β for the submarine melt rate (see chapter 4.1).

In our future scenarios when simulating subglacial discharge we ~~account~~ accounted for changes in surface runoff, basal melt, and ice sheet elevation but neglect the effect of ~~grounding line~~ ice sheet boundary retreat. This means that we route the subglacial discharge always to the present-day position of the ~~grounding line.~~ ice sheet margin to determine the amount for the specific glacier. For neighboring glaciers with a competing catchment area, a strong ice sheet retreat may strongly affect the distribution of the subglacial discharge between those glaciers (Lindbäck et al., 2015). This effect is not included in this study.

In this study, we use a single scenario for future surface runoff and SMB change, namely, a simulation with the regional model MAR nested in the global GCM MIROC5 model forced by the RCP 8.5 scenario. Among the CMIP5 models, MIROC5 simulate climate change which leads to a medium contribution of GrIS to future SLR (Calov et al., 2018). To correct for ~~possible~~ global climate model biases in ~~the future scenarios for~~ surface runoff and SMB, we ~~added the simulated~~ used anomalous approach by adding future anomalies in surface runoff and SMB simulated by MAR nested into the MIROC5 ~~anomalies~~ model to the reference climatology ~~simulated for the same period with the MAR model~~ (reference period 1961-1990) simulated by MAR forced by ERA reanalysis data. We also corrected model surface runoff and SMB for changes in surface elevation by applying the gradient method of Helsen et al. (2012) as described in Calov et al. (2018). The surface runoff R over the ice sheet (SICOPOLIS) is determined as

$$\begin{aligned} R(x,y,t) = R^{\mathrm{Clim}\ 1961-1990}_{\mathrm{MAR(REAN)}}(x,y) \quad &+ \quad \left(R_{\mathrm{MAR(MIROC)}}(x,y,t) - R^{\mathrm{Clim}\ 1961-1990}_{\mathrm{MAR(MIROC)}}(x,y)\right) \\ &+ \quad \left(\frac{\partial R}{\partial z}\right)_{\mathrm{MAR(MIROC)}}(x,y,t) \quad \Delta h_s(x,y,t), \end{aligned} \tag{17}$$

where the runoff $R(x,y,t)$ on every grid cell (x,y) at any time t is calculated by the climatological mean from 1961-1990 of MAR (forced by reanalysis data) $R^{\mathrm{Clim}\ 1961-1990}_{\mathrm{MAR(rean)}}(x,y)$ plus the anomaly of the runoff relative to the climatological mean for the same period of time obtained by MAR forced with MIROC5 $(R_{\mathrm{MAR(CMIP5)}}(x,y,t) - R^{\mathrm{Clim}\ 1961-1990}_{\mathrm{MAR(CMIP5)}}(x,y))$. For ice surface evolving in time $\Delta h_s(x,y,t) = h_s^{\mathrm{obs}}(x,y) - h_s(x,y,t)$, the vertical gradient $\left(\frac{\partial R}{\partial z}\right)_{\mathrm{MAR(MIROC)}}(x,y,t)$ determined for every time step, is additionally applied to accounting for the increase in surface runoff. The observed surface elevation h_s^{obs} of the ice sheet is taken from Bamber et al. (2013). Negative runoff values are set to zero. The correction of runoff for elevation change can be important in some case since as it was shown in Amundson and Carroll (2018), for tidewater glaciers, large and rapid changes in glacier volume can lead to a high increase in runoff due to surface lowering.

For the present-day condition, SMB is calculated from relaxation to observed surface elevation h_s^{obs}, with a different relaxation time scale τ for each glacier (see section 4.1):

$$\mathrm{SMB}\dot{B} = \frac{h_s^{\mathrm{obs}} - h_s}{\tau} \text{ in m/yr.} \tag{18}$$

~~We refer to this flux as implied SMB , calculated~~

With the latter equation we calculate the present-day SMB during the spinup experiment, similarily to Calov et al. (2018) . For future scenarios, we added the anomaly of the SMB (relative to the year 2000) to the ~~implied~~ present-day SMB. The anomaly for each grid cell of the glacier was computed from interpolation of the MAR anomaly of the centerline of the individual glacier and additionally corrected for the glacier elevation change similarly to the surface runoff (Eq. 17), but for the SMB-calculation, Δh_s is the glacier elevation change compared to present-day, assuming that the derived glacier shape from the present-day dataset is for the year 2000. The time series of cumulative SMB (without surface correction) and the annual subglacial discharge for each glacier are shown in the supporting information (Fig. S1 and Fig. ~~S2~~S4)

3.4 Fjord temperature and salinity profiles: CTD measurement and Ocean Reanalysis data

Determining vertical temperature and salinity profiles in Greenland fjords, which are the input for the plume model, is a challenging task. Measurements inside Greenland fjords are rare and do not cover all of them. For some fjords, several conductivity-temperature-depth (CTD) measurements exist, but they are mostly infrequent and often not performed close enough to the calving front. ~~Hence~~It is also important to note that T-S profiles obtained from CTD measurements have to be treated with caution because they represent only a ‘time shot’ of fjord properties which vary in time significantly (Jackson et al., 2014). However, the question arises on how to treat fjords, where no CTD measurements are available. A possible solution is to use ocean reanalysis data. Here we use the TOPAZ Arctic Ocean Reanalysis data[2] (Xie et al., 2017) and compare them with existing CTD measurements~~as well as analyze potential impact~~. Note that for all twelve glaciers used in this study the CTD measurements from the adjacent fjord are available and we use them throughout our experiments as the preferred Temperature-Salinity-profile (TS-profile). Nevertheless, to make assumptions on potential impacts of the differences between reanalysis and CTD profiles on the glacier response to climate change ~~.~~ we investigate both types of ocean data (reanalysis and measurements).

The TOPAZ dataset was produced with the ocean model HYCOM using in situ measurements and satellite data sets. It covers the time span from 1991–2013 with a spatial resolution of 12.5 km and for depths of 5, 30, 50, 100, 200, 400, 700, 1000 . . .

[2] http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=ARCTIC_REANALYSIS_PHYS_002_003

3000 m. Below 200 m depth an error $> 1°\mathrm{C}$ and > 0.1 psu can occur. The dataset does not resolve the Greenland fjords and covers only the open ocean and continental shelf.

It is known that the vertical T-S profile inside the fjords can resemble the profile in the open sea (Straneo et al., 2012; Straneo and Heimbach, 2013; Inall et al., 2014). However, often ~~a~~ the closest grid cell in the ocean reanalysis data which corresponds to the depth of the grounding line can be located hundreds of km from the fjord mouth, where other ocean conditions might prevail.

Figure 3 illustrates this problem for the Kangerlussuaq glacier: ~~much colder temperatures are measured by CTDs at depths~~ CTD measurements below 400 m show here much colder temperatures inside of the fjord ~~compare to the measurements at the same depths but~~ than far outside of the fjord. A calculation with the line plume for a subglacial discharge of 50 $\mathrm{m^3\ s^{-1}}$ shows that the melt rate ~~with~~ calculated with the TS-profile inside the fjords (50 km away from glacier) and on the continental shelf (200 km away from calving front) gives similar values of $0.5 - 0.6\ \mathrm{m\ d^{-1}}$ but when the ~~mid-fjord CTD (white dot, and dashed line at ∼ 210 km distance in panel b) would increase by 80 % when~~ melt rate is calculated using the outermost CTD ~~(white~~ outside the continental shelf (Fig. 3 red dot, at ~~–~~ ∼ 400 km distance ~~) for a typical subglacial summer discharge. Furthermore, the presence of sill(s) in the fjord and fjord circulation can affect significantly the T-S profile in the vicinity of the glacier front.~~

~~It is also important to note that T-S profiles obtained from CTD measurements have to be treated with caution because they represent only a ‘time shot’ of fjord properties which vary in time significantly (Jackson et al., 2014).~~ from the glacier and where the nearest reanalysis data with the 700 m depth are available) simulated melt reaches $3.6\ \mathrm{m\ d^{-1}}$, i.e. nearly an order of magnitude higher. Thus, choosing temperatures in the open ocean may lead to strong errors of simulated melt rates.

Due to all these uncertainties, here we test how sensitive the model response is to the chosen present-day T-S profile (CTD or Reanalysis) when carrying out future climate change simulations (Section 5).

To this aim, we first compared temperature-salinity profiles ~~of~~ constructed from the reanalysis data to available CTD measurements inside the fjords made ~~as close as possible~~ near to the glacier fronts. We investigated how to use the reanalysis data from outside the fjords to produce T-S profiles close to observations made inside the fjord. We firstly constructed the T-S profiles from ~~the reanalysis dataset~~ reanalysis data by detecting the ~~closest grid-cell~~ reanalysis grid-cells closest to the fjord mouth ~~. For comparison, we used the reanalysis data at depth~~ and with the depth of at least 200, 400 and 700 meters. We chose these maximum depths, since they corresponds vertical levels in the reanalysis data set and at the same time represent typical depths of Greenland fjords and glacier grounding lines.

Surface temperatures can be strongly influenced by a seasonal signal or other external factors and since they are less important for determine the submarine melt rate, we asses the quality of the constructed T-S profile by comparing with CTDs temperatures at the depths 200, 400 and 700m only. Figure 4 and 5 compare the temperature at these depths from reanalysis data with available CTD profiles measured over past several decades for Jakobshavn-Isbrae and Store Glacier. Since Greenland is surrounded by the continental shelf with typical depths of ~~200-400~~ 200–400 meters, most of the 700-meter depth ~~points in~~ grid-cells in the reanalysis data are located outside the ~~fjords in the deeper ocean~~shelves, far away from the glacier mouth as shown in Fig. 6 ~~for~~ on the example of Store Glacier. For ~~the~~ Store Glacier, the temperature at 700m depth inside the fjord measured by CTD is much warmer than the temperature in reanalysis data at the same depth but far away in the open ocean, which can potentially be explained by the influence of shallow continental shelf. As Schaffer et al. (2017) showed, for the Nioghalvfjerdsfjorden Glacier, the continental shelf works similarly to a sill that blocks waters ~~of~~ from greater depths and favors ~~water masses above the shelf~~ shallow water masses to pass into the fjord. For all of the investigated glaciers, we found better ~~matching profiles of reanalysis to CTD profiles if we neglected the reanalysis temperature of~~ agreement between temperature profiles constructed from the reanalysis data and CTD if we disregard temperature at 700m-depth ~~locations (mostly outside continental shelf) and used instead the 400m-depth temperature (mainly~~ in reanalysis data and use instead temperature at 400m-depth only mainly located on the continental shelf~~) for all depths below 400 m~~. If the grounding line depth was ~~larger~~ deeper than 400 m, temperatures below ~~that~~ this depth were assumed to be equal to the temperature at ~~400m- depth~~ 400m-depth in the reanalysis data. The corresponding salinity profile ~~at the same~~ below 400m-depth ~~data point was equally modulated~~ was modified the same way as the temperature profile. The location of the reanalysis data point is listed in Table 1 of the supporting information.

To produce a "present-day" reanalysis T-S profile that resembles inside-fjord conditions, we averaged temperature and salinity from reanalysis data over period ~~1990-2010 in the grid cellclosest to corresponding fjord mouth and with a depth of at least 400 m. If the fjord does not have 'blocking' sills, we extrapolate the water properties at 400m depth down to depths of the grounding lines as described above. For these investigated glaciers, we found no sills shallower than the 400m depth in the data set.~~ 1990–2010 in that particular cell. An overview of the the T-S profiles from CTD and constructed from reanalysis data is given in the supporting information (Fig. S3).

~~These~~ The T-S profiles constructed from the reanalysis data, as well as those from the CTD measurements, were used as the boundary conditions ~~in~~ for the plume model. Figure 7 shows that the ~~vertically averaged~~ temperatures derived from reanalysis data are colder than those from CTD measurements at the grounding line depth for most of the selected glaciers. This bias also remains when choosing ~~reanalysis temperature~~ temperatures from reanalysis data for the same periods when the CTD measurements were taken (not shown). Similar to the continental shelf, 'blocking' shallow sills in a fjords modify the water masses near the grounding line of a glacier. However, considering of the sill depth (Fig. S2, supporting information) when reconstructing the T-S profiles from the reanalysis data only leads to an even stronger temperature bias (dashed line Fig. S3, supporting information). Therefore, we always use the reanalysis data from 400m depth to construct T-S profiles irrespectively of the sill's depth. In the following section, we investigate how ~~these biases~~ the discrepancy of T-S profiles from CTD and reanalysis data may affect glacier response to future climate change.

For ~~the simulations of the future~~ future simulations, we prescribed simple scenarios for the ocean temperature anomalies based on temperature trends simulated by several CMIP5 models (GFDL-ESM2G, MPI-ESM-LR, and HadGEM2-CC). ~~We use again the closest 400m-depth-point neighbor of each CMIP5 model dataset~~ The trend is added to the T-S profiles (both CTD and reanalysis) for the future simulations. To determine this temperature trend we use the closest to the fjord ~~mouth. From this model cell, the temperature trend is derived with~~ model grid-cell with the depth larger than 400m for each CMIP5 model.

The temperature trends were approximated by linear regression as illustrated in Fig. 8. The ~~trend and cell location~~ Figure shows as well, the big discrepancy between the model temperatures and CTD measurement at 700m depth which was the motivation to use 400 m depth only. The temperature trends and cell locations for each glacier and CMIP5 model are listed in Table S1 of the supporting information, while the resulting minimal and maximal temperature ~~trend~~ trends for each glacier ~~is~~ are listed in Table 1.

4 Experimental setup

4.1 Selection of model parameters and model spin up

Model calibration and spinup for each glaciers have been made in two steps. First, the stand alone glacier model (without the plume parameterization) was pre-calibrated to ~~reproduce~~ best match observed surface elevation, grounding-line position (accuracy $\pm 2\,\mathrm{km}$ has been required) and velocity profile assuming a constant prescribed submarine melt rate. Dynamic parameters E, W_s, A_s and q (equation 2) were varied for this purpose (affecting basal shear stress, lateral stress, and calving front boundary condition), along with the freshwater depth in crevasses d_w and the constant melt rate m, for each glacier separately. ~~For most glaciers we use 20 or 30 years for the surface relaxation time scale τ for SMB (Eq. 18), but for some glaciers (e.g. Daugaard-Jensen) τ was set to 100 years.~~ The values of dynamic parameters and relaxation time scales for each glacier are listed the supporting information table S2.

Once the four dynamic parameters and the relaxation time scale are set ~~, we switch to~~ in our pre-calibration, we performed a set of spin-up experiment with the coupled glacier-plume model ~~. For the spinup experiments , we~~ for each glacier. In the spin-up experiments the submarine melt rate is now simulated interactively by the plume model which requires subglacial discharge and temperature and salinity profiles as input-data. We used monthly subglacial discharge for the year 2000. Vertical temperature and salinity profiles in these experiments were taken from ~~recent CTD data or~~ the reanalysis data, averaged over the time interval ~~1990-2010, and held constant. Thus, the only factors affecting submarine melt profile in~~ 1990–2010 or from recent CTD data, and were held constant in time (Fig. S3, supporting information). Nonetheless, in the spin-up ~~experiments are the depth of grounding line and the shape of~~ experiments the submarine melt rate is not constant since changes in the grounding line depth and shape of a floating tongue (if ~~present) .~~ exist) affect the submarine melt. We chose the year 2000 as the quasi-equilibrium initial state for "future" climate change simulations since the mass loss of GrIS during the last decade of 20the century was rather small (ca. 0.1 mm/yr in sea level equivalent) compare to that has been observed in the 21st century ((Vaughan et al., 2013).

We generate an ensemble ~~by varying~~ of model realizations by varying two model parameters: freshwater depth in crevasses d_w and the plume linear scaling parameter β~~(~~, (factor in a range from 0.3 to 3 that multiplies the simulated melt rate profile), which control calving rate and submarine melting, respectively. We run the coupled model for each combination of these two parameters over 100 years, so that the glacier ~~is~~ at the end of simulation was close to an equilibrium state and we exclude model versions ~~whose grounding line is further~~ which simulated the grounding line position with the error more than 2 km ~~from the observed grounding line, as diagnosed from the 1D profile,~~ or which displays a low-frequency oscillatory behaviour with advancing glacier front over the last 20 years of simulations. The list of the parameter range and number of valid realizations for CTD and reanalysis data can be found in the supporting information, Tab. S3. For the glaciers for which partition between calving and submarine melting was available from Enderlin and Howat (2013), we used this partition as an additional constraint for the model parameter combinations.

4.2 Future climate scenarios

For all future simulations, we used valid combinations of model parameters and corresponding initial conditions obtained at the end of 100-yrs spin-up runs. The anomalies of SMB were derived from the regional climate model MAR simulations as described in Section 3.3 (Fig. S1, supporting information). To compute the submarine melt rate, we use the minimal and maximal ocean temperature trends for each glacier ~~3.4~~ listed in Table 1 (Section 3.4). ~~The subglacial discharge was prescribed on~~ We prescribe the subglacial discharge for each glacier simulated off-line with a monthly time step ~~with the derived subglacial discharge data from SICOPOLIS (Calov et al., 2018) for each glacier individually 3.3 (yearly values~~ from the output of the ice sheet model SICOPOLIS. The yearly subglacial meltwater discharge is depicted in Fig. ~~S2)~~S4.

All forcing scenarios were applied for the years ~~2000 – 2100.~~ 2000–2100. In addition, we run the model for 100 years with zero anomalies of temperature, SMB, and subglacial discharge to determine unforced model drift.

To express ice volume loss in sea level rise equivalent we used the multiplication factor t under the assumption of oceans occupying $A_{\text{ocean}} = 360 \cdot 10^6\ \text{km}^2$:

$$t = \frac{\rho_{\text{ice}}}{\rho_{\text{fw}} A_{\text{ocean}}} \tag{19}$$

leads to a SLR of $2.55 \cdot 10^{-3}$ mm for 1 km^3 of ice volume V_{SLR} with the density of ice $\rho_{\text{ice}} = 917\ \text{kg m}^{-3}$, and fresh water $\rho_{\text{fw}} = 1000\ \text{kg m}^{-3}$.

The contributing ice volume V_{SLR} is ~~calculated with the total glacier volume V_{glacier} subtracted by the floating ice volume V_{fl}, ice volume under sea level V_{uSL} and the additional 12 % that - if melted- would not contribute to SLR, since the created ice-free space would be filled up by sea water (bedrock to sea level). Thus, the ice volume that only contributes to SLR is~~

$$V_{\text{SLR}} = V_{\text{glacier}} - V_{fl} - V_{\text{uSL}} \frac{\rho_{\text{sw}}}{\rho_{\text{ice}}},$$

~~with the density of ice $\rho_{\text{ice}} = 917\ \text{kg m}^{-3}$, sea water $\rho_{sw} = 1028\ \text{kg m}^{-3}$ and fresh water $\rho_{\text{fw}} = 1000\ \text{kg m}^{-3}$.~~ determined by the lost ice volume above flotation from each glacier.

5 Results

5.1 Present-day state

The simulated present-day glacier thickness and velocity profiles for the different submarine melting and calving ratios are depicted in Fig. 9 ~~.~~ with a close-up to the grounding line in Fig. S5, supporting information. Note that we allow for small floating termini, since many tidewater glaciers still evolve them on a seasonal scale and glacier fronts are also mostly undercut and thus missing a pure vertical cliff withouth any floating terminus (Bevan et al., 2012; Straneo et al., 2016; Rignot et al., 2015) . Each lines in the figure corresponds to a different combination of model parameters β and d_w listed in Tab. S3, supporting information. We found that for some glaciers, the grounding line demonstrates a high sensitivity to the melting/calving ratio, while others are primarily controlled by their bedrock topography and have relatively small ~~changes~~ variations in their grounding line position over the whole melting/~~calving-~~ calving ratio range. The Gade and Upernavik North glaciers are ~~, for example, representative~~ examples of the latter case (Fig. ~~S3). The simulated~~ S6, supporting information). In general, we observed higher velocities at the glacier terminus when higher calving rates were applied. Thus, if a glacier is not strongly buttressed by a sill or lateral resistance, different values of velocity at the glacier terminus due to different d_w strongly affect the equilibrium grounding line position. Such behavior points on the crucial role of the bedrock topography for glacier dynamics. The simulated realistic velocity profiles (Fig. 9) for Gade Glacier and Jakobshavn-Isbrae ~~required~~ lead to a slightly thinner ~~glacier than derived by the geometry of the dataset. We~~ than observed glaciers. For Jakobshavn-Isbrae we were only able to achieve stable states ~~for Jakobshavn-Isbrae with~~ using T-S profiles from the reanalysis dataset, since CTD measurements showed significantly warmer temperatures ~~,~~ and the resulting ~~higher~~ high submarine melt rate ~~in our simulations would~~ lead to the retreat of the glacier on the retrograde (upstream deepening) bedrock.

Table 2 provides a comparison ~~to~~ of simulations with observational data derived by Enderlin and Howat (2013). Only the glaciers Kong-Oscar and Docker-Smith showed a grounding line flux $\mathrm{Flx_{gl}}$ matching the observational data. All other glaciers have smaller grounding line fluxes than in Enderlin and Howat (2013). However, it should be noted that many glaciers accelerated since 2000, so it is not clear whether the fluxes reported by Enderlin and Howat (2013) are ~~true~~ directly comparable with our equilibrium fluxes. Additionally, Enderlin and Howat (2013) derived submarine melt rates for the floating termini of the glaciers ~~. Note that Enderlin and Howat (2013)~~ only since they could not account for melting of vertical glacier fronts due to limitations of their methodological approach. For a direct comparison to Enderlin and Howat (2013), we calculate $\mathrm{MeltFlx}$ of the simulated glaciers by only considering the mass loss from the floating tongue induced by submarine melting. The ratios of submarine melting to grounding line discharge of our simulations lie within the uncertainty ranges determined by Enderlin and Howat (2013). However, these uncertainties are quite large and thus allow broad parameter combinations range for some glaciers. For Jakobshavn, a high calving flux was needed in order for the coupled glacier-plume model to obtain ~~similar velocities as the~~ realistic present-day velocity profile (Fig. 9) ~~derived from the dataset. This resulted in calibrated~~ . This results in simulated glacier profiles without any floating terminus (~~and a numerical MeltFlx = 0.~~ $\mathrm{MeltFlx} = 0$), which ~~was not observed by Enderlin and Howat (2013). Thereafter~~ is not consistent with Enderlin and Howat (2013). Therefore, this simulated glacier does not match the ratio of submarine melting to grounding line discharge ratio ~~determined by~~ given in Enderlin and Howat (2013) ($\mathrm{MeltFlx}^{\star\mathrm{E}}/\mathrm{Flx}_{\mathrm{gl}}^{\star\mathrm{E}}$ Table 2). The high calving flux required ~~in order~~ to obtain the precise grounding line position might result from ~~inconsistency with~~ an error in bedrock data or ~~an information loss received by~~ a problem with the flux-weighted averaging.The Simulated Daugaard-Jensen Glacier only has a stable position with submarine melt rates lower than in Enderlin and Howat (2013).

5.2 Future simulations

After obtaining the present-day state (year 2000), we then ran ~~all valid model versions~~ the model ensemble with all valid combinations of the parameters β and d_w for 100 simulation years, applying MAR SMB anomalies, monthly subglacial discharge and two scenarios for ocean temperature change (minimum and maximum) as forcing. All results shown here have ~~the~~ a small model drift subtracted from the calculated values, to ensure that the simulated SLR is a response to the climate change. The glaciers' response to climate change strongly depends on the combination of model parameters and scenarios, resulting in high uncertainty ranges. The simulations that led to a median-range[3] SLR for each glacier is depicted in Figure 10. After 100 years, some glaciers retreat entirely and become land-terminated (Alison, Daugaard-Jensen, Kangerlussuaq, Store), while others barely show a change in the position of the grounding line (Helheim). The individual contribution of each glacier to SLR for the median-range[3] SLR experiments is shown in Fig. 11 a. Jakobshavn-Isbrae shows the most significant contribution to SLR, due to the big catchment area and large retreat, followed by Kangerlussuaq Glacier due to its full retreat.

~~These median-range SLR experiments where forced by~~ When forced by comprehensive climate change scenarios (changes in SMB with the surface elevation feedback, ocean ~~warming~~ temperature T and ~~increased~~ subglacial discharge Q~~. Together,~~) the median estimate for SLR contribution from all 12 glaciers ~~add up to almost 14 mm SLR~~ is about 17 mm at the year 2100. To quantify the ~~individual tole of the~~ role of the individual forcing factors, ~~the same model-experiments of the mid-range simulations were run excluding the~~ we perform additional set of simulation with the model versions corresponding to the median SLR response by applying different forcing factors separately. We found that from the ~~14 mm over 80~~17 mm over 70 % of SLR is caused by increased submarine melting due to the ~~additional~~ ocean warming T and increased subglacial discharge Q (Fig. 11 b). ~~Thereby~~ We found that both factors, ~~(~~T and Q~~)~~, contributed an ~~equally high amount in~~ approximately equally to SLR. The reaming ~~15 % of the 14mm SLR~~ 30 % are attributed to the glacier's response to changes in SMB (Fig. 11 b, orange ~~courve~~curve). This is quite ~~substantially~~ substantial, considering the fact that the SMB-forcing alone derived from MAR (without the glacier's response) has an almost negligible effect on SLR (Fig. 11 b, brown curve). For some glaciers, the cumulative SMB ~~(SLR ignoring glacierresponse) is even increasing~~ over the glacier's catchment area even increases towards the end of ~~this~~ 21 century (Fig S1~~). The increased mass loss by glacier dynamics origins if surface mass loss is concentrated at the glacier terminus, resulting in thinning and potentially triggering glacier retreat.~~ , supporting information). Whether this, anyhow minor SMB forcing (brown curve) is corrected for surface elevation feedback (see Section 3.3) or not, is of no significance ~~in respect to~~ for SLR (Fig. 11 b, orange and yellow curve). The increased mass loss by glacier dynamics origins if surface mass loss is concentrated at the glacier terminus, resulting in thinning and potentially triggering glacier retreat.

These estimates of the role of separate factors (changes in SMB, ocean temperature and subglacial discharge) are ~~, however, the result of the~~ valid only for the cumulative SLR of all 12 glaciers. Each individual glacier may respond differently to the ~~single forcing factor~~individual forcing factors. For instance, the Kong-Oscar Glacier (Fig. 12) is slightly gaining mass with the SMB forcing alone and shows a retreat by 10 km and contribution 1 mm to SLR only due to ocean warming. When the

[3]median for an odd number of simulations, the first value of higher half for an even number of simulation

increase in subglacial discharge is considered additionally to the ~~same~~ ocean warming, the glacier retreats another 10 km and contributes ~~to~~ approximately 3 mm ~~of~~ to SLR.

At the same time, the Yngvar-Nielson Glacier (Fig. 12) is already retreating significantly in the experiment with the SMB forcing alone. Ocean warming and increased subglacial discharge also contribute to SLR, but for Yngvar-Nielson the largest SLR contributor is the SMB change. Above we discussed only median-range scenarios, but the uncertainty ranges are crucial when ~~predicting~~ projecting future SLR. Therefore, Fig. 14 shows the first and third quartile together with the median values of the individual glacier's contributions to SLR for all sets of valid model realizations and full forcing (SMB + T (max/min) + Q) against the simulated present-day glacier discharge. Their potential SLR and grounding line retreat are listed in Table 3 and 4. Figure 14 shows a correlation between present-day grounding line discharge and the contribution to future SLR for individual glaciers. Jakobshaven and Kong-Oscar show the largest ~~uncertainties. We investigate~~ spread. To analyze whether the uncertainty ~~range results~~ ranges in SLR result primarily from the range of temperature forcing ~~($T_{\min}$/$T_{\max}$) or model parameters by distinguishing for experiments with ($T_{\min}$/$T_{\max}$)~~ or from the uncertainties in model parameters we show in Fig. 15 results of experiments forced only by $T_{\min}$ or $T_{\max}$ ocean warming scenarios. Figure 15 ~~a~~ shows that future SLR and its uncertainty related to SMB forcing alone are rather small (except for Jakobshaven-Isbrae). For glaciers like ~~Daugaard-Jensen~~ Rink and Kong-Oscar, the negative SLR originates from the increase in SMB in this region under the RCP 8.5 scenario. Since there is only one SMB forcing the spread originates from the differences in initial states cause by different fwd and β combinations. Including the forcing factors of submarine melt, T and Q, leads to a relatively high SLR contribution and ~~a~~ high SLR uncertainty ~~range~~ ranges for the Kong-Oscar, Kangerlussuaq, Rink, and Daugaard-Jensen glaciers, Fig. 15 shown by the blue columns. Since these high uncertainties arise also with the same forcing (only $T_{\min}$ or $T_{\max}$), we attribute the major source of uncertainty to the different combinations of the model parameters d_w and β. For each experiment, we also investigated whether the choice of using CTD measurements or reanalysis data for the initial ocean temperature profile had an impact on the potential SLR ~~. For the difference in SLR, we could only detect a slight increase when using reanalysis data instead of~~ (Fig. S8, supporting information). If we neglect Jakobshaven and Kong Oscar glacier (almost no valid simulations with CTD profiles available), only Helheim glacier showed a stronger increase in SLR when reanalysis data where used to construct T-S profiles. For the rest of the glaciers the choice of using reanalysis data or CTD data for ~~a few glaciers (Fig. S4)~~

T-S profiles shows only minor differences in SLR. In spite of these uncertainties, we use the median scenarios from Fig. 14 to estimate the relationship between present-day glacial discharge and contribution to SLR for the year 2100 by fitting a linear ~~function~~ regression determined with the least square method. The derived slope (~~$0.1\,\mathrm{mm\,km^{-3}\,a}$) has weak correlation (correlation coefficient 0.35)~~$0.11\,\mathrm{mm\,km^{-3}\,a}$) is statistically significant (p-values =0) and has a correlation coefficient of 0.75. With this slope and the total flux of all outlet glaciers ($\sim 450\,\mathrm{Gt/a}$ (Enderlin et al., 2014; Rignot et al., 2008)), the simple linear relationship would imply a total SLR contribution of roughly 5 cm (53 mm) from all Greenland outlet glaciers ~~.~~ at the year 2100. When choosing only four glaciers to determine the slope of the regression line, the slope can range between $0.03 - 0.16\,\mathrm{mm\,km^{-3}\,a}$ (depending strongly on the choice of glaciers , Fig. S7 supporting information) leading to an uncertainty range of roughly 15–80 mm, closely to Nick et al. (2013). These resulting regression line is however not statistically significant. This underlines the importance of choosing a sufficiently large sample size .

6 Discussion and Conclusions

For 12 ~~individual~~ selected outlet glaciers of the GrIS, we investigated their potential contribution to SLR during the 21st century for the RCP 8.5 scenario. To study the role of future changes in SMB, ocean temperature and subglacial discharge, we used a 1D flowline model ~~with~~ which includes a surface crevasse calving law and is coupled to a 1D line plume model of Jenkins (2011). In our model, the calving flux can be altered by choosing a parameter for the ~~melt water~~ freshwater depth in crevasses, and the submarine melt rate can be changed by a scaling factor. We also used two different initial temperature-salinity profiles – one derived from reanalysis data and another from in-situ measurements inside the fjords. For the present-day simulations, we varied the submarine melting and the calving parameter to obtain a glacier profile similar to observations. For all outlet glaciers, we were able to achieve a reasonable agreement between the simulated and observed present-day profiles. However, for the Jakobshavn Isbrae glacier, the simulated submarine melt and grounding line discharge ratio does not agree with that derived by Enderlin and Howat (2013), as this ice stream could not develop a floating terminus in our simulations. The melt ratio derived by Enderlin and Howat (2013) could also not be achieved for Daugaard-Jensen.

In order to simulate the future glacial contribution to SLR under the RCP 8.5 scenario, we prescribed changes in SMB and subglacial discharge based on results of the regional climate model MAR. Anomalies of ~~near-fjord~~ ocean temperatures from CMIP5 ~~global climate models served~~ climate models were used to generate minimum and maximum scenarios for the ocean temperature change until year 2100. Simulated SLR contributions for the year 2100 compare well to values from Nick et al. (2013) for Jakobshavn Isbrae. The ~~Kangerlussuaq Glacier exceeds the SLR~~ conservative estimations of Jakobshavn Isbrae contribution to SLR obtained with the 3D model of Bondzio et al. (2017) also lie within our uncertainty range. For the Kangerlussuaq Glacier our estimates for SLR contribution exceed estimation of Nick et al. by 2 mm, while for the Helheim Glacier our SLR estimations are below the ~~estimations~~ estimation of Nick et al. (2013). In our simulations all glaciers experience a grounding line retreat which is found as well by Nick et al. (2013) but was not simulated by Peano et al. (2017) . This discrepancy might be related to the coarse spatial resolution (5 km) of Peano et al. (2017) model (especially for the deep and narrow trough in Jakbobshavn) or processes upstream of the glacier might have counterbalanced the glacier retreat, which we could not simulate with a 1D flowline model. The difference to Nick et al. (2013) can be explained by their different treatment of ~~future calving fluxes (freshwater depth~~ calving processes (in their model freshwater depth in the crevasses was linked to ~~future~~ runoff) or submarine melting (~~excluding~~ Nick et al did not account on the influence of changing subglacial discharge). Also, Nick et al. (2013) used the surface elevation and velocity profile from the center line and took the width ~~as~~ of the whole catchment area, whereas at Jakobshaven Isbrae, the width was constrained to the width of the trough and the lateral flux was added. By contrast, we use a flux-weighted average of the whole glacier catchment area to represent each individual glacier.

~~we use a flux-weighted average of the whole glacier catchment area, whereas Nick et al. (2013) used for e.g. Jakobshaven Subrea a narrow channel and added lateral flow.~~

We also investigated how ~~various~~ different forcing factors influence the simulated future SLR. For the ensemble of the 12 glaciers, SLR is ~~sevenfold~~ over threefold larger when the changes in subglacial discharge and ocean temperature were added to changes in SMB. This underlines the critical role of oceanic warming for future GrIS contribution to SLR. Moreover, we found significantly larger SLR when the subglacial discharge is allowed to increase in the scenarios. In fact, the amount of SLR attributed to subglacial discharge is similar to the SLR attributed to an increased ocean temperature. Thus, for future projections, both factors affecting submarine melt rate – subglacial discharge and ocean temperature – need to be taken into account. It should also be noted that our 1D flowline model is based on a crevasse depth calving law and thus does not account for undercut calving or buoyancy-driven calving (Benn et al., 2017), which in turn is strongly influenced by submarine melting. This mechanism might act as a further amplifier of glacial mass loss that is not ~~reflected~~ accounted for in our results.

Our experiments also reveal large uncertainty ranges, primarily attributed to the different combinations of the two model parameters that determine submarine melting and calving fluxes. Nonetheless, the simulated melt/calving ratios lie within the uncertainty range of observations, and reducing the uncertainties with more precise observational data would probably improve future simulations. On the other hand, our results ~~were~~ are not significantly affected by the choice of CTD or reanalysis data when defining the initial ocean temperature and salinity ~~profile~~profiles. This suggests that accurate process-based models and observational constraints on submarine melt and calving are more important when making projections about future ~~retreat~~ response of Greenland outlet glaciers to climate change. Additional uncertainty related to dynamic parameters and topography data (bedrock, width) are not included in this study.

Overall, we obtain a total Greenland glaciers SLR contribution of approximately 5 cm when assuming a linear relationship between the glacier's present-day grounding line discharge and ~~and future sea level rise. Our result~~ their contribution to future SLR. Our estimate for SLR is lower than ~~the estimate~~ in Nick et al. (2013) (6.5-18.3cm) partly due to the fact that we ~~included smaller marine-terminating~~ took into consideration also smaller marine terminating glaciers. As Goelzer et al. (2013) argues, these glaciers probably become land-terminating faster than glaciers with a large grounding line discharge and have less mass influenced by ice-ocean interaction. Therefore ~~we think that our~~ our upscaling method for ~~this emissions~~ the strong climate change scenario should not be used past the year 2100. Our simulations considered a constant catchment area for each glacier and did not account for potential changes in lateral inflow from the ice sheet interior. Such increased mass inflow could result in a smaller grounding line retreat ~~and thus decrease our SLR contribution estimate. However,~~ but an increased inflow would also result in a broadening of the catchment area, as Goelzer et al. (2013) indicate, which could increase ice sheet mass loss further upstream. The full impact can only be assessed with experiments in which outlet glaciers and the parent ice sheet are fully coupled. Additionally, the 1D flowline model treat lateral processes in a simplified manner, so that more complex bedrock geometries (e.g. branching of glaciers, individual sills, unsymmetrical valley forms) are poorly represented in these estimations. For a first approximation, though, we treat the SLR of 5 cm as additional to that simulated with coarse resolution GrIS ice-sheet models, since the cumulative SMB forcing (without glacier response) over the glaciers' area is negligible. Some inconsistency arises from the fact that the database used to initialize the glaciers at the year 2000 are actually based on the measurements made in 2008/2009, but the total contribution of GrIS to global seal level rise during the first 8 years of the 21st century was only about 3 mm and glaciers contributed not more than half of that. Thus this inconsistency has only a minor effect on our moderate approximation of 5 cm.

By adding the 5 cm contribution of outlet glaciers to the 8.8 cm (mid-range scenario) simulated by Calov et al. (2018) for the year 2100 using an ice sheet model under the same climate scenario, we arrive at a total GrIS contribution 13.8 cm ~~.~~ (10.3 -16.8 cm from lower sample size range).

This implies that the dynamical response of Greenland's outlet glaciers to ~~global warming~~ climate change can increase GrIS contribution to SLR in 2100 by over 50 %.

Author contributions. J.B designed the study together with A. G.. M.P. wrote the glacier model in fortran and provided 1D topography data for the 12 glaciers of this study. J.B. coupled the numerical plume model to the glacier model, and implemented the surface-correction method. Together with S.B, R.C and M.W, J.B. created the projected subglacial discharge and surface-mass balance data set for each glacier respectively. J.B. carried out the experiments, created figures and wrote the manuscript, supported by all co-authors.

Competing interests. The authors declare no competing interests.

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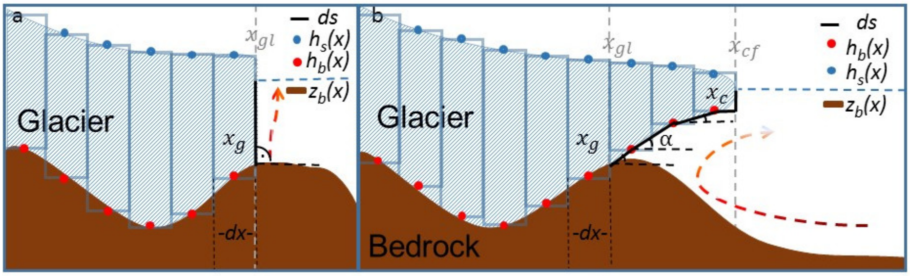

Figure 1. Visualiszation of 1D glacier model with the staggered grid for a) a tidewater glacier and b) a glacier with floating tongue. Red dots indicate where the ~~values~~ depth of glacier ~~bottom~~ base h_b ~~are~~ is defined and blue dots where surface elevation h_s of the glacier is defined. They are calculated at dx/2 - the half width of each grid cell. Last grounded cell has the coordinate x_g and last floating cell has the coordinate x_c. The grounding line gl_x is determined at the border of the last grounded cell, where the flotation criterion is not yet achieved. After the grounding line, the calculation of submarine melt along the distance ds (thick, black line) is performed with the line plume model. For a floating tongue (b) every grid cell may have a different angle for ~~ds~~ the slope of glacial base while for a tidewater glacier (a) the angle is set to 90 degrees. The bedrock elevation z_b (brown, thick line) is equal to h_b for the grounded part and is deeper for the floating part of the glacier.

~~Retreat of median-range[3] SLR scenario for RCP 8.5 forcing scenarios (SMB and ocean temperature and subglacial discharge) for all 12 glaciers at 2100 (orange). Corresponding initial states are depicted in grey. Daugaard-Jensen, showed full retreat with over 80 km.~~

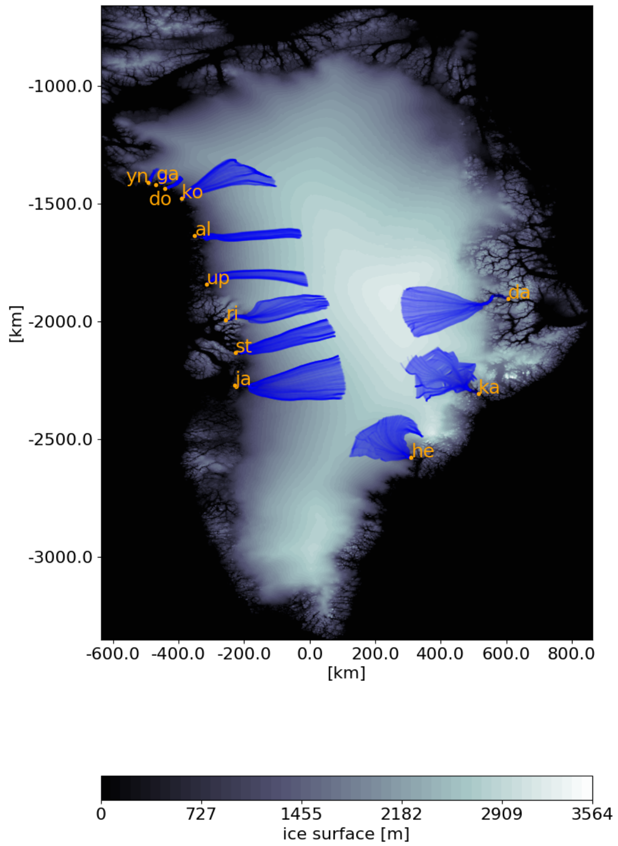

Figure 2. Terminus location (orange dot) with the catchment area (blue) of the twelve investigated glaciers: Alison Glacier (al), Daugaard-Jensen Glacier (da), Docker-Smith Glacier (do), Gade (ga) Helheim Glacier (he), Jakobshavn-Isbrae (ja), Kangerlussuaq Glacier (ka), Kong-Oscar Glacier (ko), Rink-Isbrae (ri), Store Glacier (st), Upernavik North Glacier (up), Yngvar-Nielsen Glacier (yn)

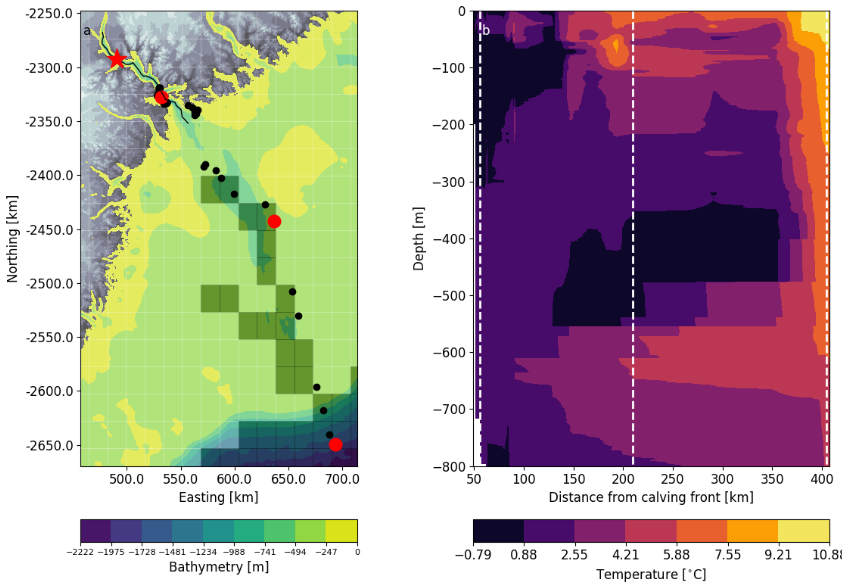

Figure 3. a) Bathymetry around Kangerlussuaq glacier (red star indicates glacier terminus). Black dots indicate the location of the CTD measurements ~~in~~ made in September 2004. ~~White~~ Red, thick dots show the location of CTD profiles used for the submarine melt rate calculations in the text and are indicated as white dashed lines in panel b). Closest CTD. Grid indicates the resolution of the reanalysis data and grey shaded squares show which reanalysis data points have a ~~minimum~~ depth of ~~400m~~at least 400 m. b) Vertical temperature distribution as a function of the distance from the glacier terminus, obtained by interpolation ~~od~~ of the CTD profiles. White dashed lines correspond to the position of the ~~white-marked~~ red-marked CTD positions in panel a and give for a subglacial discharge 50 m^{3}s^{-1} an average melt rate of 0.5, 0.6 and 3.6 m/d (from left to right).

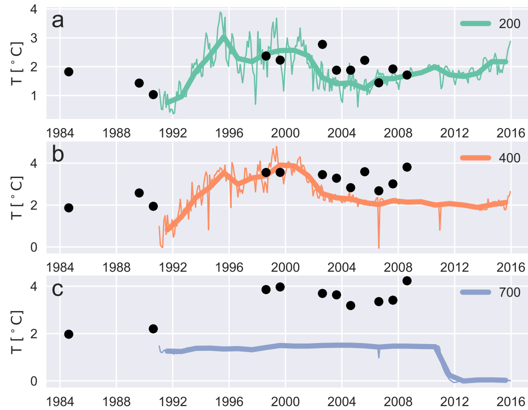

Figure 4. Monthly (thin lines) and annual mean (thick lines) of ocean temperature from reanalysis data of the closest point to fjord of Jakobshavn-Isbrae that has a minimum depth of a) 200m b) 400m and c) 700m depth. Location of these points differ due to the different area coverages for the corresponding depths (700m is mostly outside of continental shelf). Black dots show CTD measurements at the same depth but inside or close to the fjord.

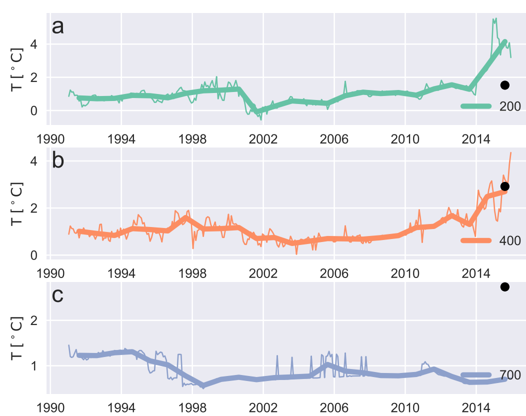

Figure 5. Same as in Fig. 4 but for Store Glacier.

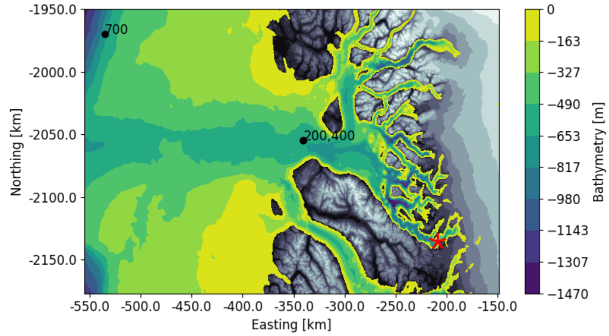

Figure 6. Bathymetry and bedrock data close to the terminus of Store Glacier (red star). The labels 200, 400 and 700 indicate were the detection points of the reanalysis data closest to the glacier with the depth of 200 m, 400 m and 700 m were located.

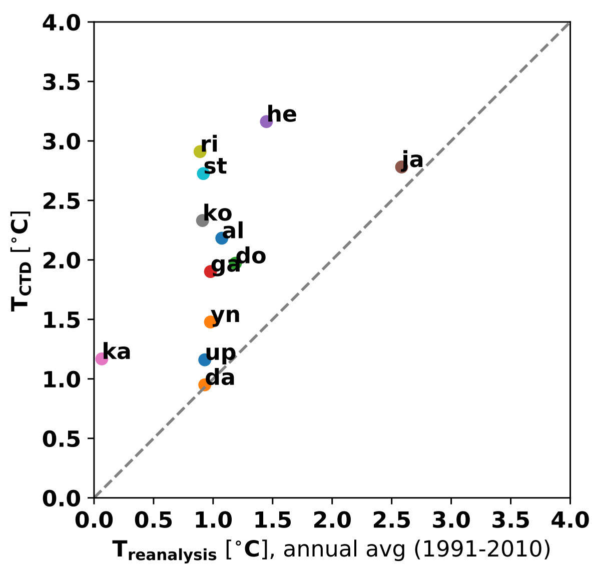

Figure 7. ~~Depth-averaged temperature~~ Temperature at the grounding line depth of CTD measurements closest to glacier front, inside the fjords (y-axis) and temperatures from Reanalysis data ~~of extrapolated 400m-depth points,~~ from the nearest grid-cell with depth 400m averaged from 1991 -2010 (x-axis) for all 12 glaciers: Alison (al), Daugaard-Jensen (da), Docker-Smith (do), Gade (ga), Helheim (he),Jakobshavn Isbrae (ji), Kangerlussuaq (ka), Kong Oscar (ko), Rink Isbrae (ri), Store (st), Upernavik (up), Yngvar Nielsen (yn).

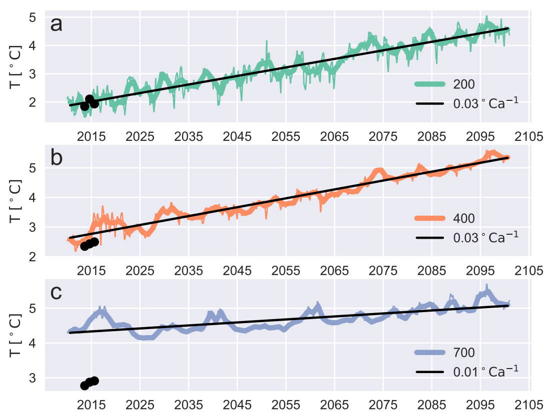

Figure 8. Monthly ocean temperature and centennial trend from the CMIP5 model MPI-ESM-LR in the closest ~~points~~ grid-cells to the fjord of Rink Isbrae that have a ~~model~~ depth of at least a) 200m b) 400m and c) 700m depth. Black dots show CTD measurements at the same depth but inside the fjord.

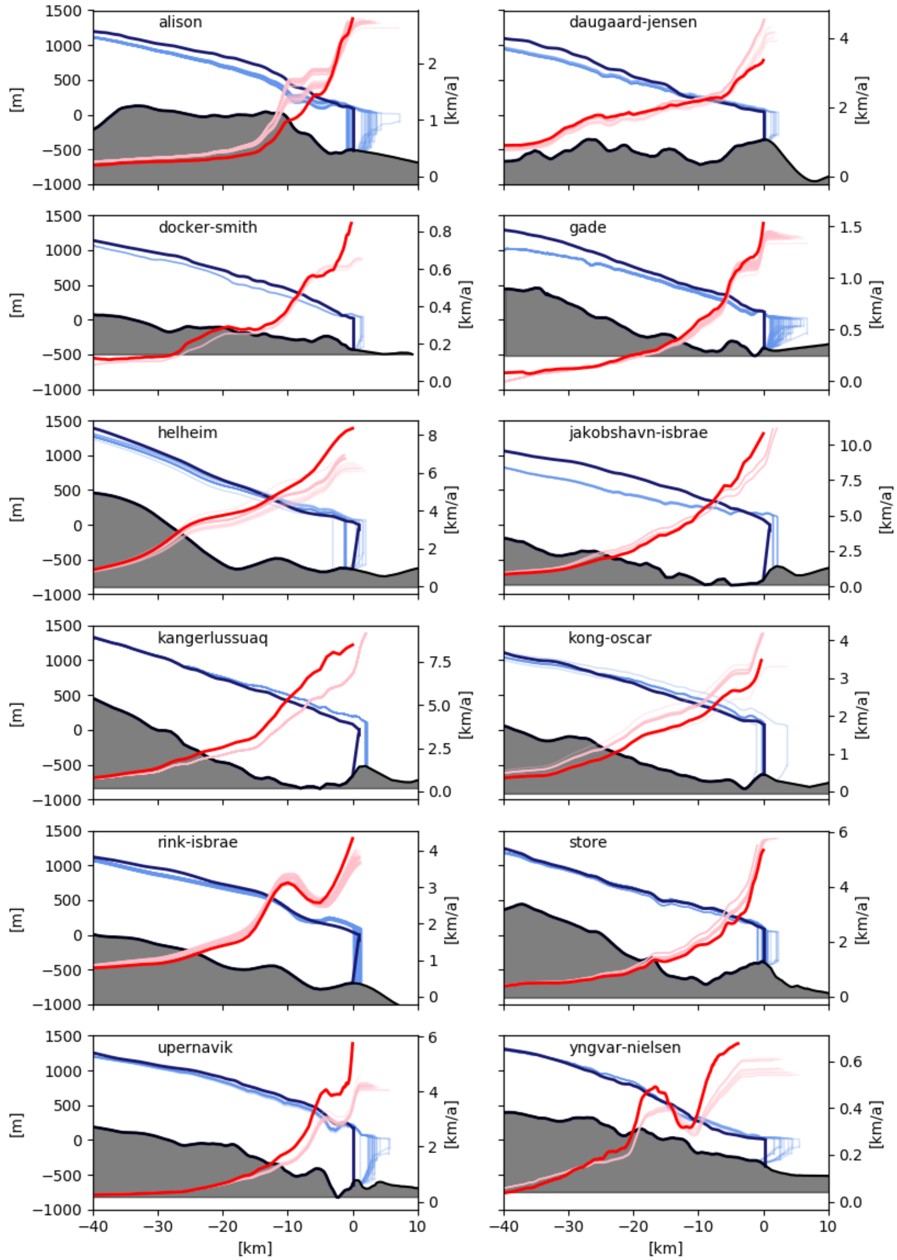

Figure 9. ~~Glacier thickness~~ Simulated glacier elevation (~~thick,~~ light blue) and velocity profile (~~thick,~~ light red) for the last 40 km to the grounding line ~~from the derived geometry of the dataset published~~ plotted together with observational data (dark blue and dark red) by Morlighem et al. (2014) and Rignot and Mouginot (2012). ~~The resulting profiles of all stable states simulated~~ Bedrock data is derived by the ~~line-plume glacier-flowline model are depicted~~ flux weighted average over the whole catchment area. Number of simulations is given in ~~transparent lines~~Tab. S3, supporting information.

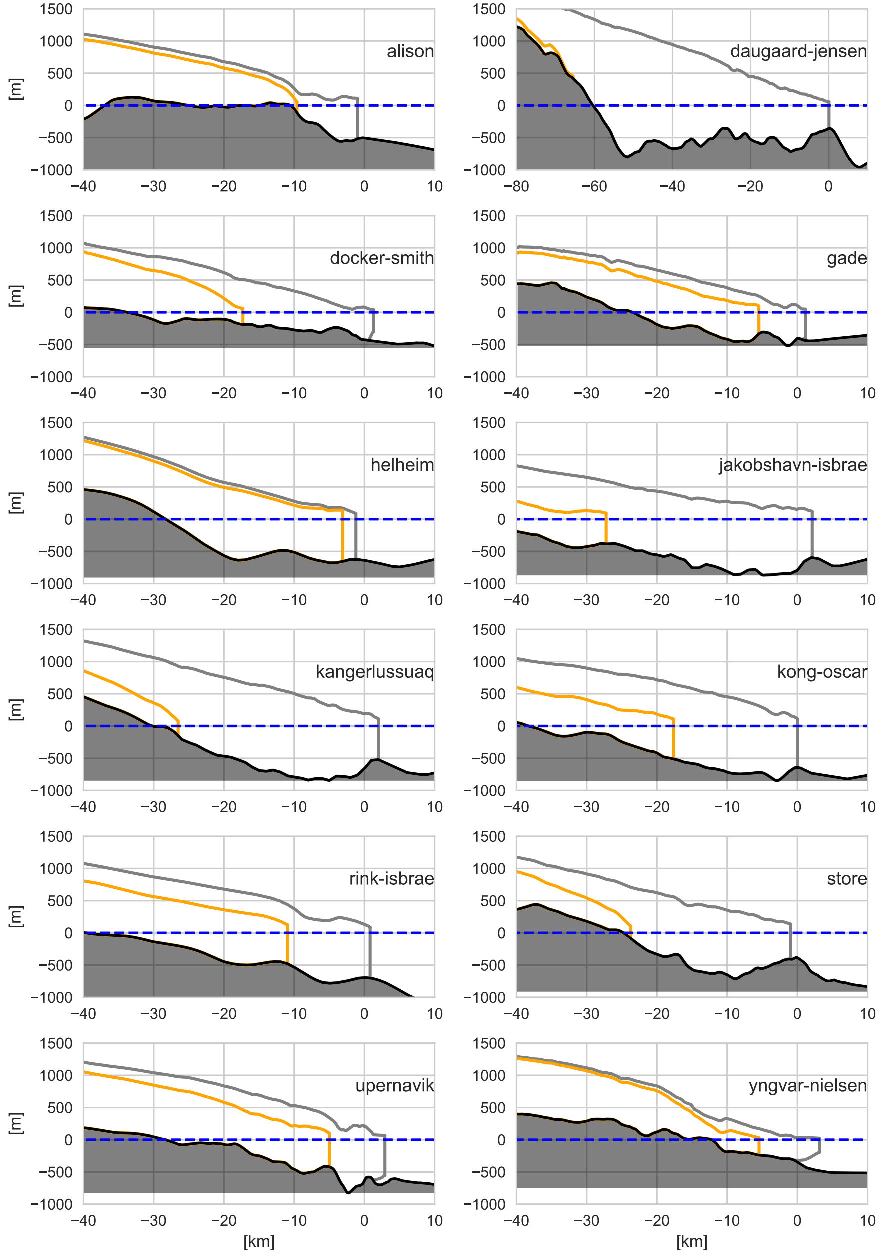

Figure 10. Retreat of median-range [3] SLR scenario for RCP 8.5 forcing scenarios (SMB and ocean temperature and subglacial discharge) for all 12 glaciers at 2100 (orange). Corresponding initial states are depicted in grey. Daugaard-Jensen, showed full retreat with over 80 km.

[3] median for an odd number of simulations, the first value of higher half for an even number of simulation

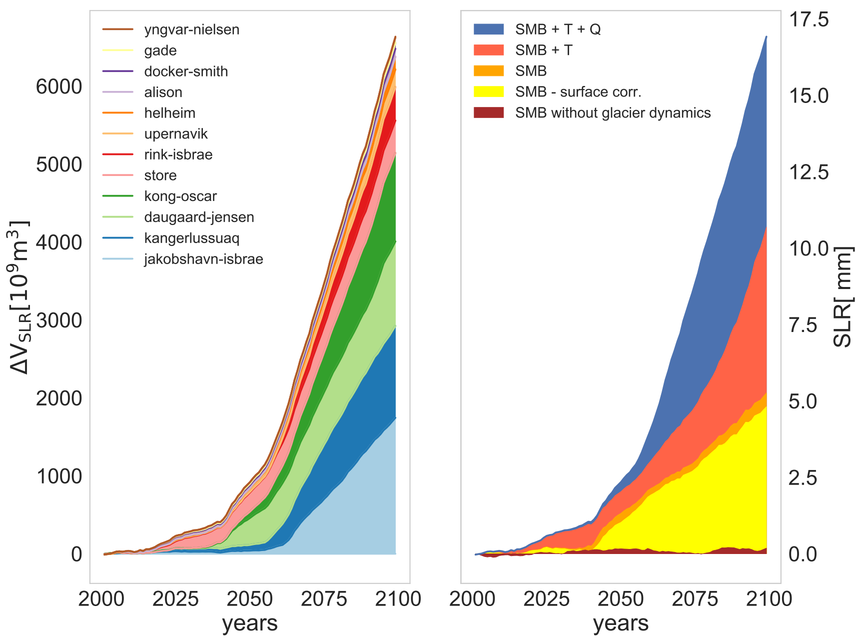

Figure 11. Cumulative sea level rise of median-range[3] SLR scenario from Fig. 10 for all 12 glaciers. ~~The~~ Left panel: Individual glaciers' response to complete future forcing scenario (~~smb~~SMB, subglacial discharge Q and ocean temperature T in blue)~~, without subglacial discharge~~. Right panel: the role of individual forcing factors for all glaciers.SMB + T + Q (blue) SMB + T ~~;~~ (pink), ~~with~~ SMB forcing only (orange) and ~~excluding~~ SMB without the surface elevation feedback (~~SMB, no dz;~~ yellow). The SMB forcing ~~vom~~ from MAR is calculated over the whole present-day catchment area of all glaciers (brown).

[3] median for an odd number of simulations, the first value of higher half for an even number of simulation

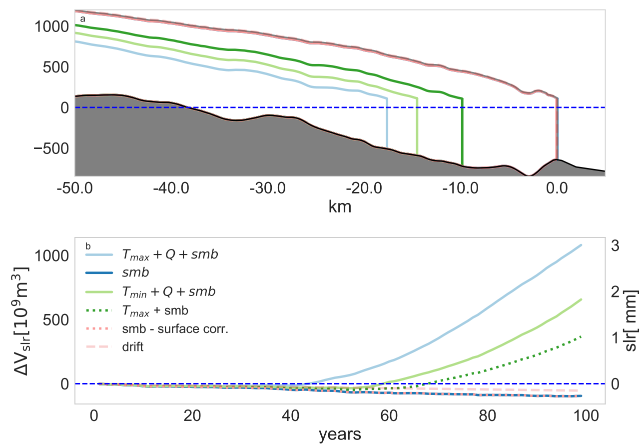

Figure 12. a) Kong-Oscar Glacier with a representative medium-slr retreat scenario applying forcing factors as subglacial discharge Q, ocean temperature T, surface mass balance smb with and without accounting for surface elevation correction (smb - surface corr.) for the medium SLR scenario. The corresponding SLR of each experiment is displayed in panel b).

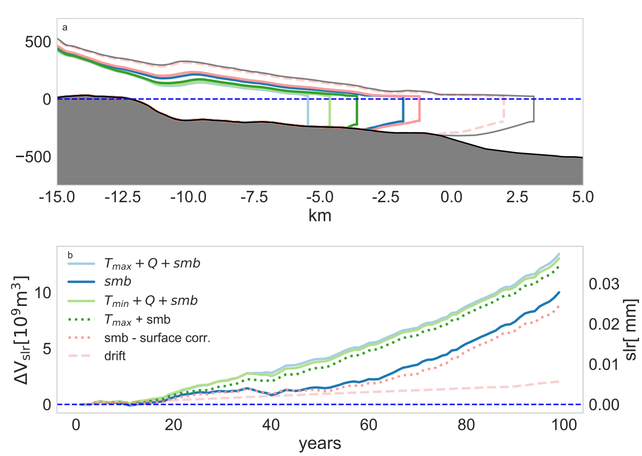

Figure 13. ~~Same~~ a) Yngvar Nielsen Glacier with a representative medium-slr retreat scenario applying forcing factors as ~~12~~ subglacial discharge Q, ocean temperature T, surface mass balance smb with and without accounting for surface elevation correction (smb - surface corr.) for the medium SLR scenario~~but for Yngvar Nielsen Glacier~~. The corresponding SLR of each experiment is displayed in panel b).

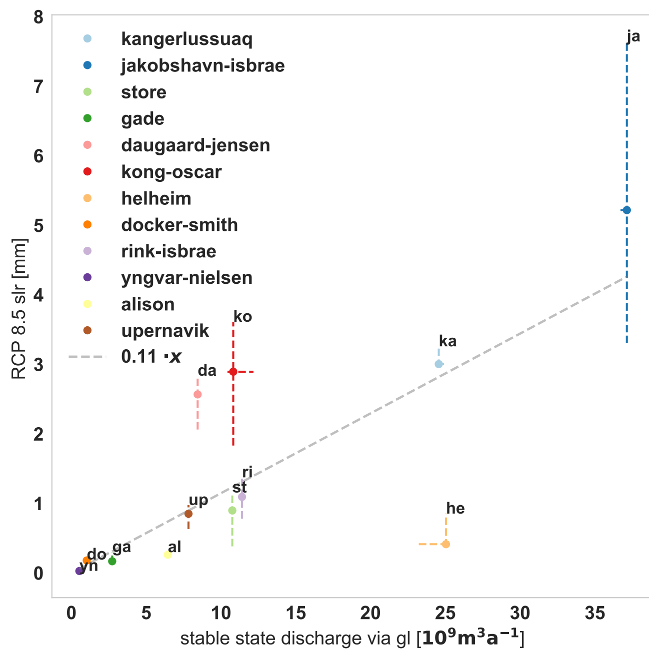

Figure 14. First to third quartile (median indicated with a dot) of contribution to SLR at 2100 under RCP 8.5 for each glacier from Table 3 as a function of the present-day grounding line discharge. The future simulations were forced by changes in SMB, subglacial discharge and minimal and maximal ocean temperature trend (Tab. 1). Grey dashed line, indicates a linear ~~function of the present-day grounding line discharge in future SLR for 2100~~ regression obtained with an ordinary least square ~~model~~ method from the median values. Slope and p-value are $0.1\,\mathrm{mm\,km^{-3}}$ a and ~~0.279~~ $9 \cdot 10^{-5}$, respectively. The correlation ~~is weak with a correlation~~ coefficient ~~with 0.35~~is 0.75.

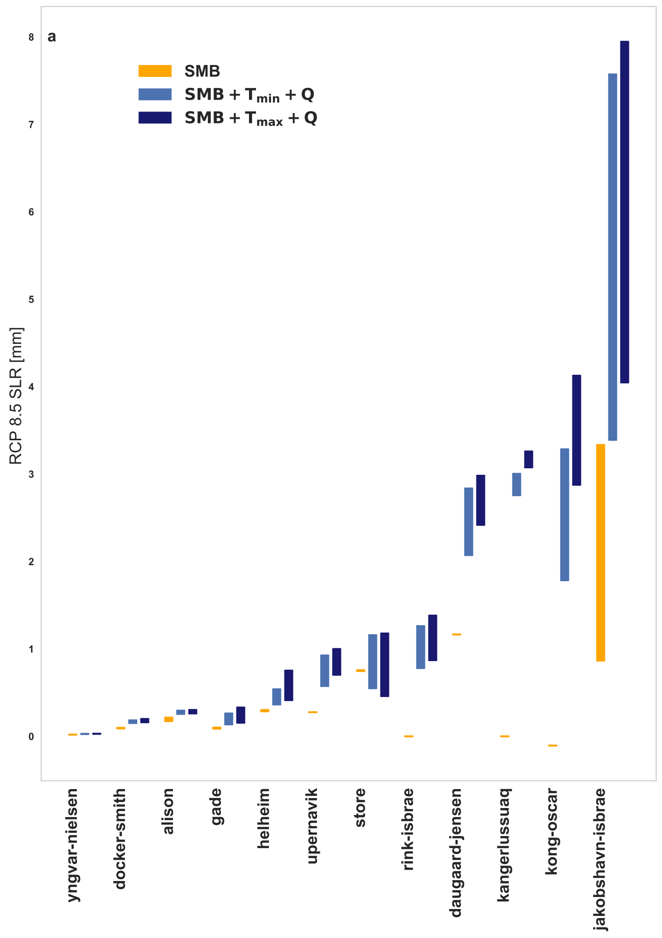

Figure 15. First to third quartile of contribution to SLR for each glacier. Future RCP 8.5 scenarios were either forced with SMB changes only (orange) or changes in SMB, ocean temperature ($T_{\min}$ and $T_{\max}$) and subglacial discharge (blue).

Table 1. Minimal and maximal ocean temperature trend ~~derived by~~ for three CMIP5 Models ~~close~~ derived from the grid-cells closest to each glacier fjord ~~at~~ with minimum 400m depth. Detailed information are listed in table S1, supporting information.

glacier name	$\Delta T_{\mathrm{min}}(^{\circ}\mathrm{C}/100\mathrm{a})$	$\Delta T_{\mathrm{max}}(^{\circ}\mathrm{C}/100\mathrm{a})$
Daugaard-Jensen	3	5
Helheim Glacier	2	3
Jakobshavn Isbae	2	4
Kangerlussuaq Glacier	3	4
Rink Isbrae	1	3
Store Glacier	1	3
Kong Oscar Glacier	1	3
Alison Glacier	1	3
Upernavik Isstrom	1	3
Yngvar Nielsen	1	3
Docker Smith Glacier	1	3
Gade Glacier	1	3

Table 2. Each investigated glacier with the mean grounding line discharge from observation $\mathrm{Flx}_{\mathrm{gl}}^{\star\mathrm{E}}$ (Enderlin and Howat, 2013) and from the stable state simulations $\mathrm{Flx}_{\mathrm{gl}}$ as well as the number of stable simulations (#). The melt flux range for floating termini from all present-day simulations $\mathrm{MeltFlx}$ and from the observational data $\mathrm{MeltFlx}^{\star\mathrm{E}}$ is calculated with the error ranges in Enderlin and Howat (2013) but with the condition $0 < \mathrm{MeltFlx}^{\star\mathrm{E}} < \mathrm{Flx}_{\mathrm{gl}}^{\star\mathrm{E}}$. The respective ratio of melt flux /grounding line discharge in % is listed in the last to columns. ~~Glaciers with~~ The sign * ~~indicate were~~ indicates glaciers for which the melt rate partition of the simulation does not overlap with the ~~error~~ range of Enderlin and Howat (2013). Melt fluxes of are for floating tongue and thus $\mathrm{MeltFlx} = 0$ indicates tidewater glaciers. Store Glacier is not examined in Enderlin and Howat (2013).

glacier	$\mathrm{Flx}_{\mathrm{gl}}^{\star\mathrm{E}}$ 10^9 $[\mathrm{m}^3/\mathrm{a}]$	$\Delta\mathrm{Flx}_{\mathrm{gl}}\mathrm{i}$ 10^9 $[\mathrm{m}^3/\mathrm{a}]$	$\Delta\mathrm{MeltFlx}^{\star\mathrm{E}}$ 10^9 $[\mathrm{m}^3/\mathrm{a}]$	$\Delta\mathrm{MeltFlx}$ 10^9 $[\mathrm{m}^3/\mathrm{a}]$	$\mathrm{MeltFlx}^{\star\mathrm{E}}/\mathrm{Flx}_{\mathrm{gl}}^{\star\mathrm{E}}$ [%]	$\mathrm{MeltFlx}/\mathrm{Flx}_{\mathrm{gl}}$ [%]	#
alison	6.83	6.25 - 6.55	0.82 - 6.41	0.00 - 4.77	12 - 94	0 - 76	54
daugaard-jensen*	9.34	7.82 - 8.44	4.12 - 9.34	0.00 - 2.06	44 - 100	0 - 26	22
docker-smith	1.06	1.05 - 1.07	0.00 - 0.87	0.22 - 0.66	0 - 82	21 - 62	5
gade	4.85	2.63 - 2.81	0.00 - 4.85	0.17 - 2.14	0 - 100	6 - 77	55
helheim	29.16	22.84 - 25.94	0.19 - 6.90	0.00 - 8.39	1 - 24	0 - 36	28
jakobshavn-isbrae*	43.03	36.81 - 37.14	21.11 - 32.91	0.00 - 0.00	49 - 76	0 - 0	11
kangerlussuaq	38.80	24.51 - 24.58	0.00 - 6.83	0.00 - 0.00	0 - 18	0 - 0	39
kong-oscar	11.86	10.34 - 12.86	3.06 - 6.28	0.00 - 2.64	26 - 53	0 - 26	16
rink-isbrae	10.95	11.20 - 11.73	0.00 - 6.85	0.00 - 0.00	0 - 63	0 - 0	64
store	-	10.55 - 11.29	-	0.00 - 1.73	-	0 - 16	67
upernavik north	17.12	7.48 - 7.84	5.81 - 11.20	0.03 - 5.92	34 - 65	0 - 78	21
yngvar-nielsen	0.69	0.53 - 0.56	0.00 - 0.69	0.08 - 0.42	0 - 100	15 - 76	11

Table 3. Median, first and third quartile of SLR contribution from each glacier under RCP 8.5 scenario (~~smb~~SMB, subglacial discharge and ocean temperature (min and max)). Values are corrected from drift. Negative values in SLR indicate ~~smb~~ SMB gain.

	slr [mm]		
glacier	median	first quartile	third quartile
alison	0.26	0.26	0.30
daugaard-jensen	2.73	2.12	2.84
docker-smith	0.18	0.15	0.19
gade	0.17	0.14	0.30
helheim	0.41	0.38	0.85
kangerlussuaq	3.00	2.96	3.26
kong-oscar	2.89	1.83	3.61
rink-isbrae	1.10	0.79	1.38
store	1.05	0.40	1.16
upernavik	0.85	0.63	0.98
yngvar-nielsen	0.03	0.03	0.03
jakobshavn-isbrae	5.22	3.30	7.65
sum	17.90	12.99	22.55

Table 4. Median, first and third quartile of grounding line retreat from each glacier under RCP 8.5 scenario (~~smb~~SMB, subglacial discharge and ocean temperature (min and max)). Values are corrected from drift.

	grounding line retreat [km]		
glacier	median	first quartile	third quartile
alison	9.21	8.69	10.77
daugaard-jensen	60.80	28.99	62.21
docker-smith	15.13	14.23	16.49
gade	5.85	4.62	15.17
helheim	1.52	1.10	9.63
kangerlussuaq	28.52	28.44	28.53
kong-oscar	17.65	14.61	18.63
rink-isbrae	11.07	10.90	11.18
store	17.59	3.99	23.21
upernavik	17.43	12.79	17.72
yngvar-nielsen	4.69	4.28	5.22
jakobshavn-isbrae	38.57	19.85	40.53
avg	19.00	12.71	21.61