Overview

This study seeks to determine which mechanism of frontal and submarine melt and ice-ftont calving primarily drove the retreat of Sermeq Kujalleq glacier between 1985 and 2018. Ensemble modelling was performed whereby the magnitude of previously published frontal and submarine melt rates were adjusted alongside the calving stress threshold of a tensile stress based calving law. The calving law was further adapted in an attempt to account for backstresses imparted by ice melange. Optimised parameters were then used to assess potential future behaviour of Sermeq Kujalleq up to 2100.

Although the question of whether oceanic melting or calving processes were the ultimate drivers of Sermeq Kujalleq's retreat is of great interest, there could be more detail given in methods used in the study in order to justify how physically meaningful the employed parameters are. Further, improvement to existing figures as well as the addition of further figures may help with the clarity of results interpretation and the conclusions drawn from the study. With further clarification added to address the comments below I believe this manuscript would be valuable to the community and recommend it for publication.

We would like to thank the reviewer for their insightful remarks. Below is our initial response, broken down by remark. Original review comments are shown in black, while our answers are shown in red.

Comments

Line 8: Are all the drivers coming from the ocean? There is no mention of atmospheric drivers. Can it be discussed in the methodology why atmospheric drivers are not considered here and the title of the paper should be more specific on this.

There is atmospheric forcing through SMB but it is held constant to the multi-decadal mean obtained from RACMO throughout the simulation. In Methods, line 90, we note that there exists much greater interannual variability in oceanic forcings than in atmospheric forcings. We will clarify this in text.

Line 49-50: 'the process of acquiring necessary observations…' Which observations? And why do icebergs make it more challenging?

Observations of environmental variables such as mélange density, detailed calving catalogues, geometry of calving front. Icebergs act as physical obstacles which may complicate data collection methods, especially near the glacier front. We will clarify why these observations are relevant and their associated difficulties more clearly in text.

Line 77: I'd find it informative to include a figure of the study area. Where are the fast flowing regions? Where is 'deep in the catchment area' and what are the flow speeds here?

We will include a supplemental figure showing simulated SK's velocity field from MEASURES data and make appropriate references when discussing flow speeds.

Line 78: How are different areas of the domain chosen for coarsening / refinement?

Using ISSM's built in bidemnsional anisotropy mesh generator, we refine the mesh using a metric based off the product of bedrock slope and surface velocity (strain rates). The range of individual element edge length ranges from 400m-4km (high-low strain rates). We will expand upon the methods section to include this information.

Line 82 – 85: 'A linear-viscous sliding relation…' How does the inversion arrive at appropriate coefficients for the sliding law? I don't understand what is meant by 'which have been scaled down to give a smooth transition between both data sets', please expand on this.

We will expand on the process for how we determine sliding coefficients for the Budd-Glenn sliding law in the methods. We first patch 2 surfaces of 1985 and 2009 and assume ds/dt is proportional to velocity as to offset the 2009 velocities. We then composite the 1985 and 2009 velocity series. We will clarify this information in the methods.

Line 86-87: What are the boundary conditions elsewhere in the domain?

At the catchment boundaries, we impose ice temperatures from Seroussi et al., [2013]. Along the computational domain's lateral boundary, observed ice flow velocities are imposed and water pressure at the calving front. We will clarify this information in the methods.

Line 95: Can you explain the correction that has been applied in more detail? I don't understand what has been done from this sentence.

We utilize a surface elevation model of Sermeq Kujalleq's lower elevation area from 1985, derived from photogrammetry [Korsgaard et al., 2016]. We address data gaps inland by incorporating surface elevation data from the Greenland Mapping Project [Howat et al., 2014], adjusting this data to match the earlier dataset with an elevation offset that corresponds to current ice flow velocities [Rignot and Mouginot, 2012]. We will clarify this information in the methods.

Line 112: Is the linear decrease in calving stress threshold supported by previous studies, observations or physics?

The linear variation in calving stress threshold is a simplified realization of the effects of mélange weakening/strengthening on buttressing the calving front, which has been posited as a possible explanation for observations indicating mélange weakening and breakup in concert with ocean temperature seasonality, rather than atmospheric temperatures [Kehrl et al. 2017, Bevan et al. 2019, Joughin et al. 2020]. Our main justification for this assumption of ice mélange weakening in response to heightened temperatures and we use a linear sensitivity a simplest case option and for easy comparison to other linear sensitivities assumed in this study.

Line 114: Equation 3 – explain what sigma_max and sigma_min used in this equation are.

Sigma_max represents the maximum stress threshold corresponding to the minimum temperature within our temperature time series. Sigma_min representns th minimum stress threshold corresponding to the max ocean temperature. When ocean temperatures are warmest, we assume mélange is at its weakest and therefore proclivity for calving is intensified and vice versa. We will clarify and standardize usage of parameters in methods.

Line 129: Equation 4 – A and B are not explained. Are these tuning parameters? What are their values?

A is a tuning parameter with a value of 3E-4 (non-dim) and B is to ensure that heat flux does not vanish in the absence of melt water and has a value of 0.15 [Rignot et al., 2016.] We will clarify this information in text.

Line 139: Equation 5 – Add a table with values of parameters such as gamma_T etc.

We will add a table with variables and their respective values at the end of the methods section.

Lines 144-150: How the parameter space is varied may be better suited in the respective sections 2.2 and 2.3 rather than in the section detailed the mismatch score.

We will move this section regarding how we vary parameter space earlier to sections 2.2 and 2.3.

Line 145: 'we choose a range of 0-4x the empirical parametrisations' What are the choices of range based on? Are there any observations / literature to support this?

There are no literature based reason for this. This range was selected following a series of experiments within different ranges to capture as much variability in simulation output. We do this instead to capture various forms of interplay between ocean-temp dependent calving and submarine and frontal melting. We will elaborate on this more in the methods.

Line 146: 220-360kPa – same comment as above. Please justify the choice of ranges. Figure 2 shows results up to 350kPa, should this be 360kPa?

Results are only shown up to 350kPa. Beyond 360 kPa, the calving front and grounding line do not retreat at all and did not yield valuable information. We will include this information in the methods.

Figure 1: It would be helpful to know where the grounding line is and how this moves through the simulation. A lot of the results interpretation talks about the ice tongue and it would be very helpful to visualise how the extent of the ice tongue changes and a note to emphasise when it disintegrates.

We will include a supplemental figure showing the grounding line and calving front migrations for our best performing model.

Figure 1: Is ‘Elevation’ shown colour map ‘Bed elevation’?

Yes, elevation refers to bed elevation. We will correct this in the figure.

Figure 1: I find the figure somewhat difficult to interpret. As the modelled and observed calving fronts deviate quite widely it is difficult to tell which dashed lines should be compared to which solid lines from the colour scheme. Is it necessary to present data from every year or can the colour scheme be adjusted to make it more clear which modelled and observed calving fronts should be compared?

We believe that presenting data from each year highlights the differences in rates of retreat between periods of rapid and slow retreat. As such we include one front per year. We have experimented with plotting fronts more sparsely or labeling individual contours, but these missed presenting years in which critical retreat occurred or cluttered the figure so that it was difficult to read.

Line 154: No need to write ‘within’ as well as ‘less than’

Fixed in text

Line 155-162: I don’t understand the scoring system from the description given here. Please can this be addressed and made more explicit?

We added in text, for each observational data point, we calculate the difference in surface area between observed and simulated geometries. We then take the RMS of the vector of differences to derive an overall mismatch “score”. We will clarify this in the methods.

Line 161: How is the error vector (starting and end point) defined?

Refer above. The first timepoint corresponds to the mismatch at t1(1985) of the simulation and final timepoint corresponds to tend(2018). We will clarify this in the methods.

Line 168: ‘thin lines’ should be dashed lines

Corrected in text

Line 169: ‘thick lines’ should be solid lines

Corrected in text

Line 177: For discussion on the disintegration of the ice tongue, no grounding line locations are shown in figure 1 so the location / extent of the ice tongue is not clear

Noted in text that grounding line is located at a specific distance upstream from calving front. We will also provide a visual reference of grounding line migration as a supplemental figure.

Line 186-187: It would be interesting to see the evolution of tensile stress seen at the terminus of both branches over the years. Can a figure be used to illustrate this?

Added figure to supplemental info showing glacier stress at key times.

Figure 2. It is not clear why the specific parameters are presented in panels b – d.

Corrected in text to standardize symbols for parameters and explain meanings.

Figure 2: Is M_f the same as M_fr (given in equation 4)?, Is M_s the same as M_sm (given in equation 5)?

Corrected in text to standardize symbols for parameters and explain meanings.

Figure 2: What is the red dot displayed on panel b? Best overall fit? Please add explanation to caption.

Corrected in text to indicate best fit model.

Figure2: alpha_ms and alpha_mf are not defined anywhere, are these the same as M_s and M_f?

Corrected in text to standardize symbols for parameters and explain meanings.

Line 198-199: '…than suggested by the two-equation parameterisation.' Add citation for this.

We will add a reference here [Rignot et al., 2013]

Line 204: With the best fitting simulation requiring high sensitivity to frontal melting, how do the ablation rates m_fr and c compare in the parameter space? It would be interesting to see whether the calving rates and frontal melt rates vary on the same magnitude.

This is a great suggestion and we thank the reviewer for highlighting it. We will include a supplemental figure showing the following, a single panel plot similar to 3a, but for all 3 parameters and for every simulation in the parameter space where line color would correspond to RMSE. For example, panel a) calving panel b) frontal melt and panel c) submarine melt sharing the same legend

Figure 3: Panel B. Observed area change time series vs modelled area time series would be more informative.

We will correct in figure 3.

Line 218: ‘SK maintained a floating ice tongue ahead of its terminus’. Is the terminus not the front of the ice tongue at this point?

SK maintained a floating tongue which at some locations extended upwards of 10km ahead of its grounding line. We will clarify this in text.

Line 239: Need figures to support this statement

We will include a reference to figure 3a.

Line 230: Calving rate in this study is defined by speed, stress and stress threshold. Temperature can only play a role through these variables, why would we expect calving fluxes to be controlled by temperature? The calculation of ‘calving flux’ should also be defined as different definitions appear in the community (not as unique as ‘grounding line flux’)

We will clarify in text the units we use for our calving flux. We expect that, in our simulations, our calving fluxes would increase as temperature increases due to the temperature-calving stress threshold dependence we impose. We note here however that there is a lag between the initial temperature increase in’96 and the subsequent increase in calving flux in 2010. We will clarify this information in text.

Line 269: With the runs up to 2100, significant terminus retreat is observed. Is the same mesh considered as had been described previously? Is the mesh resolution at these retreated grounding line locations still 400m?

Mesh resolution scales from 400m at the initial front to 4km inland. While the mesh is certainly coarser than 400m by the time it retreats far upstream, the short time step, enforcement of CFL in the model and use of a level set to define the terminus position ensures that the model is still doing a good job representing terminus fluxes. We will clarify this information in the methods.

Line 272: How is the range of threshold values 260-437kPa chosen? Same comment as on Line 146.

We will discuss in supplemental info why we chose range of 260-437kPa.

Line 278-279: ‘even if ocean temperatures returned to the coldest values achieved during the historical period over the next 80 years, the rapid acceleration of calving and retreat would likely continue unabated’ – this may well be due to a limitation with the calving law which should be acknowledged, rather than necessarily being a direct indication of what may happen in the future.

This is a good point, and pretty much what we were trying to get across with these simulations. In these simulations, even when ocean temperatures returned to their 1985 values, we see that SK continues to retreat. However, our interpretation of this result is not necessarily that this implies SK is in the midst of an irreversible calving-driven retreat in reality, but rather that simulations which represent calving in such a simplistic way will tend to produce irreversible retreat, but this may not be the case if mélange is realistically represented. We will clarify this information further in text.

Figure 4: caption – What is the 2100 run? The ensemble members running from 1985 – 2100? The caption could be more concise.

We will clarify what our 2100 runs correspond to more clearly in text. We will include a new caption: Calving fluxes of 1985-2100 run ensemble members. Between 2018-2100, maximum calving stress threshold is set to a multiple of the calving stress threshold at 2018.

Line 305: sigma_max or sigma_thr?

We will correct to SIGMA_MAXthr

Line 315-320: See 'Parsons et al, 2024, Quantifying the Buttressing Contribution of Sea Ice to Crane Glacier' for proposed methodology for assessing the terminus stress regime with/without adjoining melange elements. Could a similar method be used in this study to account for changes in the terminus stress regime with the presence of melange?

We will cite Parsons et al., 2024 as a potential way of quantifying buttressing impact in text.

Figure 5: Panel A. Improve the quality of this figure. It appears to have been stretched.

We will improve figure 5's quality.